CALIFORNIA
ENERGY
COMMISSION

ENERGY INNOVATIONS SMALL GRANT PROGRAM
Renewable Energy Technologies

PROCESS FOR CONVERTING SEWAGE SLUDGE AND MUNICIPAL SOLID WASTES TO CLEAN FUELS

FEASIBILITY ANALYSIS

December 2001
P600-01-012

Gray Davis, *Governor*

CALIFORNIA ENERGY COMMISSION

Prepared By:
Hal Clark
Grant Program Administrator

Prepared For:
California Energy Commission
Energy Innovations Small Grant Program

Researcher:
Radon Tolman

Philip Misemer
Grant Program Manager

Terry Surles
Deputy Director
Technology Systems Division

Steve Larson
Executive Director

LEGAL NOTICE

PREFACE

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million of which $2 million/year is allocated to the Energy Innovation Small Grant (EISG) Program for grants. The EISG Program is administered by the San Diego State University Foundation under contract to the California State University, which is under contract to the Commission.

The EISG Program conducts four solicitations a year and awards grants up to $75,000 for promising proof-of-concept energy research.

PIER funding efforts are focused on the following six RD&D program areas:

- Residential and Commercial Building End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research

The EISG Program Administrator is required by contract to generate and deliver to the Commission a Feasibility Analysis Report (FAR) on all completed grant projects. The purpose of the FAR is to provide a concise summary and independent assessment of the grant project using the Stages and Gates methodology in order to provide the Commission and the general public with information that would assist in making follow-on funding decisions (as presented in the Independent Assessment section).

The FAR is organized into the following sections:

- Executive Summary
- Stages and Gates Methodology
- Independent Assessment
- Appendices
  - Appendix A: Final Report (under separate cover)
  - Appendix B: Awardee Rebuttal to Independent Assessment (Awardee option)

For more information on the EISG Program or to download a copy of the FAR, please visit the EISG program page on the Commission's Web site at:
http://www.energy.ca.gov/research/innovations

or contact the EISG Program Administrator at (619) 594-1049 or email
eisgp@energy.state.ca.us.

For more information on the overall PIER Program, please visit the Commission's Web site at
http://www.energy.ca.gov/research/index.html.

Executive Summary

Introduction

Most new power plants being installed in California are Gas Turbine Combined Cycle (GTCC) plants that burn increasingly expensive natural gas and fuel oil to produce electricity at up to 60% efficiency. These plants can be installed in less than half the time and at less than half the cost of new coal-fired plants and Integrated Gasification Combined Cycle (IGCC) plants that use cheap dirty fuels, but are less than 42% efficient. A new system is needed to adapt the new plants to cheaper fuels, while maintaining their efficiency and environmental performance.

This project researched the feasibility of a supercritical water gasification (SCWG) process to convert compost made from municipal solid wastes and sewage sludge to clean energetic gases. The expectation is to reduce the fuel costs of GTCC plants and to improve both efficiency and environmental performance of existing steam power plants.

Objectives

1. Determine the feasibility of using SCWG to gasify composted municipal solid waste/sludge, consisting of at least 23 wt% solids, with a minimum 96% conversion of carbon to gas.
2. Verify through visual inspection that no significant erosion, corrosion and deposition occurred inside the bench-scale SCWG system.
3. Assess the feasibility of recycling resulting liquids for "zero effluent" design.
4. Update and validate simplified thermodynamic computer simulation and a life cycle cost models that can be used to predict system performance with various fuels.

Outcomes

1. Use of SCWG to gasify composted municipal solid waste/sludge is feasible by a wide margin:
   - We produced a pumpable slurry mixture containing 40 wt% solids, exceeding the target goal by 74%.
   - The bench-scale system converted over 98% of the carbon in the slurry to energetic gases and steam, including clean pressurized methane, hydrocarbons and carbon oxides in less than one minute, which is twice as fast as the target time.
2. No noticeable erosion, corrosion or deposition was observed in the test equipment.
3. Total suspended solids in the liquid effluent was less than 10%, supporting the feasibility of recycling liquids for slurry preparation after filtering to provide a "zero effluent" design. No toxic materials were produced that would limit disposal of the residue in a landfill.
4. A thermodynamic computer simulation model and a life cycle cost model were prepared, however, there was insufficient funding in the current project to validate the models over a range of inputs, including the test data. Equilibrium compositions were assumed to be sufficiently close to expected commercial operations to provide preliminary predictions of system performance. Results of the computer simulations included:

- Projected 62% thermal efficiency to electric power for the entire proposed hybrid plant. Projected efficiency for retrofit in an existing steam power plant is 52%.
- Projected capital costs of $1,100/kWh for a new hybrid plant, with projected cost of baseload power generation at $100/MWh.
- Projected capital costs of $500/kWh for retrofit to an existing GTCC plant, with projected cost of baseload power generation at $50/MWh.
- Retrofits for repowering existing Steam plants are competitive with GTCC plants burning natural gas costing $3.00 or more /million Btu.

Conclusions

1. The test results support the continued investigation of composted municipal waste as an economical fuel source for GTCC and existing steam power plants.
2. We demonstrated that compost made from municipal solid wastes and sewage sludge can be made into a slurry with 40 wt% solids, which significantly increases the range of applications, including the production of valuable byproducts, such as hydrogen. This mixture tended to clog in the ¼" preheater tube which was completely alleviated by changing to 3/8" tubing. This problem is not expected in larger tubes.
3. The project successfully demonstrated that the compost slurry can be used in a SCWG process to produce energetic gases and steam, including approximately 35% gaseous hydrocarbons and hydrogen, the largest fraction being methane. The remaining 65% of the carbon in the feed was converted mainly to CO_2 and a small amount of CO. The CO_2 can be separated for reduced emissions. It is unknown what effect compost grinding had on residence time for gasification. It is also unknown what impact scaling up the reactor tubes will have on the SCWG process.
4. Sufficient yield data was collected to determine gas composition, perform a carbon balance and perform a preliminary evaluation of recycling liquids after filtering for slurry preparation. While no corrosion, erosion or deposition was observed after running the tests, the tests conducted were not designed to accurately assess those effects over long-term testing.
5. Environmentally, based on residence time and projected full scale HRSG tubes, a standard module of 100 HRSG tubes per 25 MW turbine can consume an estimated 170 tons of composted municipal solid waste per day, reducing it to approximately 34 tons of inorganic material.
6. The results of the computer simulation models are encouraging in terms of supporting an economic case for commercialization; however, the models still include many assumptions that remain to be validated.

Benefits to California

This project contributed to the Public Interest Energy Research (PIER) program objective of improving energy cost of California electricity through the use of inexpensive biomass fuels. The project also contributes to the PIER objective of improving the environmental risk by diverting waste streams away from landfills.

Successful commercialization of SCWG technologies could promote business opportunities in several industries, including process development, waste disposal, electrical generation, pollution control and transportation fuels.

Recommendations

The next research step is to scale up the critical elements of the SCWG system to eliminate the problems associated with the bench-scale system used in the current project and to conduct a series of tests that more accurately represent anticipated operational conditions. General Atomics in San Diego is currently constructing a scaled up SCWG test rig with full-scale HRSG reactor tubes that would be suitable for answering the outstanding technical questions. The following technical questions need to be answered:

- Test a full range of slurry concentrations in full size reactor tubes to identify the associated impact on steam and fuel gas production.
- Identify the optimum level of grinding required (if any) for trouble free gasification in full size reactor tubes,
- Confirm slurry distribution in a 10-tube inlet manifold for scale-up to a commercial plant,
- Confirm that the energy balance for SCWG is the same using full size reactor tubes,
- Evaluate the longer-term potential for corrosion, erosion or deposition,
- Test condensate for yield and quality and cleaning methods for recycle to slurry preparation,
- Test ash for beneficial use or land filling,
- Test mild operating conditions for byproduct yields and quality, including liquid hydrocarbons and carbon,
- Refine computer models and economic feasibility analyses for retrofit to existing gas turbines and boilers, and
- Collect and test fuel gases for combustibility in existing gas turbines, fuel cells and boilers.

Stages and Gates Methodology

The California Energy Commission utilizes a stages and gates methodology for assessing a project's level of development and for making project management decisions. For research and development projects to be successful they need to address several key activities in a coordinated fashion as they progress through the various stages of development. The activities of the stages and gates process are typically tailored to fit a specific industry and in the case of PIER the activities were tailored to be appropriate for a publicly funded energy research and development program. In total there are seven types of activities that are tracked across eight stages of development as represented in the matrix below.

Development Stage/Activity Matrix

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8
Activity 1								
Activity 2								
Activity 3								
Activity 4								
Activity 5								
Activity 6								
Activity 7								

A description the PIER Stages and Gates approach may be found under "Active Award Document Resources" at: http://www.energy.ca.gov/research/innovations and are summarized here.

As the matrix implies, as a project progresses through the stages of development, the work activities associated with each stage needs to be advanced in a coordinated fashion. The EISG program primarily targets projects that seek to complete Stage 3 activities with the highest priority given to establishing technical feasibility. Shaded cells in the matrix above require no activity, assuming prior stage activity has been completed. The development stages and development activities are identified below.

Development Stages:	Development Activities:
Stage 1: Idea Generation & Work Statement Development	Activity 1: Marketing / Connection to Market
Stage 2: Technical and Market Analysis	Activity 2: Engineering / Technical
Stage 3: Research & Bench Scale Testing	Activity 3: Legal / Contractual
Stage 4: Technology Development and Field Experiments	Activity 4: Environmental, Safety, and Other Risk Assessments / Quality Plans
Stage 5: Product Development and Field Testing	Activity 5: Strategic Planning / PIER Fit - Critical Path Analysis
Stage 6: Demonstration and Full-Scale Testing	Activity 6: Production Readiness / Commercialization
Stage 7: Market Transformation	Activity 7: Public Benefits / Cost
Stage 8: Commercialization	

Independent Assessment

For the research under evaluation, the Program Administrator assessed the level of development for each activity tracked by the Stages and Gates methodology. This assessment is summarized in the Development Assessment Matrix below. Shaded bars are used to represent the assessed level of development for each activity as related to the development stages. Our assessment is based entirely on the information provided in the course of this project, and the final report. Hence it is only accurate to the extent that all current and past work related to the development activities are reported.

Development Assessment Matrix

Stages / Activity	1 Idea Generation	2 Technical & Market Analysis	3 Research	4 Technology Develop-ment	5 Product Develop-ment	6 Demon-stration	7 Market Transfor-mation	8 Commer-cialization
Marketing								
Engineering / Technical								
Legal/ Contractual								
Risk Assess/ Quality Plans								
Strategic								
Production. Readiness/								
Public Benefits/ Cost								

The Program Administrator's assessment was based on the following supporting details:

Marketing/Connection to the Market. The project has submitted a Preliminary Business Plan detailing the product development to market. While the plan is quite detailed and pertinent to the issues of Gate 3, we believe that it presents a somewhat optimistic timeline from "proof of feasibility" to a marketable product. Future activity should include revision and updates to this plan as the California energy picture has changed since this plan was authored, particularly the cost of natural gas. Additionally, potential commercializers should be contacted and interviewed to provide feedback from currently identified potential customers as well as to identify additional customers and stakeholders.

Engineering/Technical. This project successfully demonstrated that composted municipal solid waste/sewage sludge can be gasified using the Supercritical Water Gasification process. Additional testing is needed to understand and optimize the operating parameters for the process. The Program Administrator concurs with the recommendations from the executive summary that the HRSG reactor tube test rig under construction at General Atomic, which permits full control over the SCWG process, is the appropriate test bed for evaluation of the following open issues.

1. **Test a range of slurry concentrations.** Conduct tests over the useful range of slurry concentrations using full-scale (One inch diameter) HRSG reactor tubes. Tests should be designed to provide the following information:

- Identify the relationship between solids concentration and associated impact on steam and fuel gas production,
- Determine the optimum level of grinding required (if any) for trouble free gasification in full size reactor tubes,
- Determine the energy balance for SCWG using a range of slurry concentrations and full size reactor tubes,
- Determine if the fuel gases produced require additional processing to be used in existing gas turbines, fuel cells and boilers.

2. **Evaluate the Effluent.** Determine the potential of a zero-effluent design:
   - Test condensate for yield and quality and cleaning methods for recycle to slurry preparation,
   - Test ash for beneficial use or land filling,
   - Test mild operating conditions for byproduct yields and quality, including liquid hydrocarbons and carbon,
3. **Hardware Specific Investigations.** Design factors to be considered:
   - Evaluate the longer-term potential for corrosion, erosion or deposition,
   - Confirm slurry distribution in a 10-tube inlet manifold for scale-up to a 100 tube commercial plant,
4. **Test Planning.** Develop criteria and test plans for field experiments,
5. **Provide updated estimates.** Refine computer models and economic feasibility analyses for retrofit to existing gas turbines and boilers.

Legal/Contractual. Intellectual property related to the core technology is protected by patent. Identified commercializers should be asked to submit existing and projected sales data as part of the process for selecting a commercializer for this technology.

Environmental, Safety, Risk Assessments/ Quality Plans. Some assessment of environmental impact has been done related to diversion of municipal solid waste and sewage sludge waste streams and the recycling of process water. Initial drafts of the following Quality Plans are needed prior to initiation of Stage 4 development activity; Reliability Analysis, Failure Mode Analysis, Manufacturability, Cost and Maintainability Analyses, Hazard Analysis, Coordinated Test Plan, and Product Safety**.**

Strategic. This product has no known critical dependencies on other projects under development by PIER or elsewhere. It is believed to be unique to this project with limited or no impact on other PIER projects.

Production Readiness/Commercialization. General Atomics Corp. in San Diego has been selected as the Research, Development and Demonstration collaborator. Their commitment to this project is evidenced by the SCWG pilot plant under construction in their "State of the Art" testing laboratory located at their Sorrento Valley facility in San Diego. Top candidates for commercializing partner remain to be identified and interviewed. However, a plan to accomplish selection of the partner has been identified.

Public Benefits. PIER research public benefits are defined as follows:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary public benefit offered by the proposed technology is to make electrical energy more affordable in California. This will be accomplished by reducing the cost per KW of power generated by using composted municipal solid waste and sewage sludge as a fuel source in a combined cycle plant using super critical water gasification. A conservative lifecycle cost analysis was performed using the following assumptions:

- 50 MW combined cycle power plant using SCWG process
- 30 year plant life
- Capital cost of $1200/KW
- O&M cost of $.005/KW
- Thermal efficiency of 50%
- 75% availability
- Fuel costs of $2.24Mil/year ($1.00/Mbtu)

Based on the above assumptions the proposed plant could produce power for approximately $.024/KW which is competitive. The major urban areas in California could conservatively divert sufficient municipal solid wastes and sewage sludge to support ten 50MW plants.

The proposed cost of fuel ($1.00/Mbtu) assumes that tipping fees will fund the majority of the costs associated with processing the waste streams into compost. This assumption is a risk factor that would need to be further assessed in the business plan.

Additional benefits to California include:

- Diverting biomass from the landfills reduces greenhouse gasses which can escape into the atmosphere and toxic effluents which can contaminate water supplies. A report prepared by the National Renewable Energy Laboratory, "The Value of the Benefits of U.S. Biomass Power," by G. Morris, places a value on this benefit alone at $0.047/KW generated from biomass.
- Use of renewable biomass for fuel produces a reliable fuel source and reduces California's dependency on limited domestic or expensive foreign fossil fuels.
- Use of MSW and sewage sludge for fuel reduces the volume of this waste material by 80%, which extends the life of existing landfills and reduces the need for new landfills.

Program Administrator Assessment:

After taking into consideration: (a) research findings in the grant project, (b) overall development status as determined by stages and gates and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for follow on funding within the PIER program.

Receiving follow on funding ultimately depends upon: (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation and (c) successful evaluation of the proposal.

Appendix A: Final Report (under separate cover)

Appendix B: Awardee Rebuttal to Independent Assessment (none submitted)

ENERGY INNOVATIONS SMALL GRANT (EISG) PROGRAM

EISG FINAL REPORT

PROCESS FOR CONVERTING SEWAGE SLUDGE AND MUNICIPAL SOLID WASTES TO CLEAN FUELS

EISG AWARDEE
Worldwide ENVIRONMENTAL ENERGY SYSTEMS INC.
589 Crestwood Drive
Oceanside, CA 92054-1478
Phone: (760) 967-8494
Email: wweesi@pacbell.net

AUTHORS
Radon Tolman, Principal Investigator
Jerry Parkinson, Consultant
Bill Rickman, Project Manager

Grant #: 99-04
Grant Funding: $75,000
Term: September 1999 – July 2001
PIER Subject Area: Renewable Energy Technologies

Legal Notice

This report was prepared as a result of work sponsored by the California Energy Commission (Commission). It does not necessarily represent the views of the Commission, its employees, or the State of California. The Commission, the State of California, its employees, contractors, and subcontractors make no warranty, express or implied, and assume no legal liability for the information in this report; nor does any party represent that the use of this information will not infringe upon privately owned rights. This report has not been approved or disapproved by the Commission nor has the Commission passed upon the accuracy or adequacy of the information in this report.

Inquires related to this final report should be directed to the Awardee (see contact information on cover page) or the EISG Program Administrator at (619) 594-1049 or email eisgp@energy.state.ca.us.

Acknowledgements

The facilities and equipment provided by General Atomics as subcontractor in San Diego is gratefully acknowledged, in addition to the services of Bill Rickman, Project Manager, and Dave Hazlebeck, Principal Engineer, and staff. The modeling work performed by Dr. Jerry Parkinson of Los Alamos, NM, is also greatly appreciated.

EISG Awardee

This project was awarded to ENVIRONMENTAL ENERGY SYSTEMS INC. (EESI) of Santa Fe, NM. The Company is registered with the Secretary of State of California as Worldwide ENVIRONMENTAL ENERGY SYSTEMS INC. (wwEESI) in accordance with California law.

Table of Contents

Appendices

List of Figures

List of Tables

Abstract

The purpose of this project was to research the feasibility of a supercritical water gasification (SCWG) process to convert compost made from municipal solid wastes and sewage sludge to clean energetic gases without oxygen. The goal is to reduce fuel costs for gas turbine combined cycle (GTCC) power plants and to improve both efficiency and environmental performance of existing steam power plants.

A lab-scale tubular reactor system was tested without oxygen at General Atomics (GA) in San Diego to convert compost to clean gases. Compost was prepared in a commercial aerobic digester and cured for odor-free handling and shipment. Test conditions were above the supercritical conditions of water, 221 bar (3205 psia) and 374 C (705 F). A high-density pumpable and stable slurry of over 40 wt.% solids was prepared at GA. The tubular reactor converted over 98% of the carbon in the slurry to hydrogen, methane, hydrocarbons and carbon oxides in less than one minute. No tar formation or corrosion of the equipment was observed.

A computer simulation model was prepared to simulate a hybrid power system. It predicts 62% thermal efficiency with minimum emissions and zero liquid effluents. Preliminary life-cycle cost analyses predict that electricity costs can be reduced to less than $50/MWh by retrofitting to existing natural gas fired combined cycle plants for base load service.

A pilot plant is planned to test the reactor tubes at full size. Development promises to reduce fuel costs, while solving waste disposal problems for California and worldwide applications.

Key Words:

Biomass, compost, supercritical water, slurry, gasification, sewage sludge, refuse

Executive Summary

Introduction

Most new power plants being installed in California are Gas Turbine Combined Cycle (GTCC) plants that burn increasingly expensive natural gas to produce electricity at up to 60% efficiency. These plants can be installed in less than half the time and at less than half the cost of new coal-fired plants and Integrated Gasification Combined Cycle (IGCC) plants that use cheap dirty fuels, but are less than 42% efficient. A new system is needed to adapt the new plants to cheaper fuels, while maintaining their efficiency and environmental performance.

This project researched the feasibility of using a supercritical water gasification (SCWG) process to convert compost made from municipal solid wastes and sewage sludge to clean energetic gases without oxygen. The expectation is to reduce the fuel costs of GTCC plants and to improve both efficiency and environmental performance of existing steam power plants.

Objectives

1. Determine the feasibility of using SCWG to gasify composted municipal solid waste/sludge, consisting of at least 23 wt% solids, with a minimum 96% conversion of carbon to gas.
2. Verify through visual inspection that no significant erosion, corrosion and deposition occurred inside the bench-scale system.
3. Assess the feasibility of recycling resulting liquids for zero liquid effluents.
4. Update and validate simplified thermodynamic computer simulation and life cycle cost models that can be used to predict system performance with various fuels.

Outcomes

1. Use of SCWG to gasify composted municipal solid waste/sludge is feasible by a wide margin:
    - We produced pumpable slurry mixture containing 40 wt% solids, exceeding the target goal by 74%.
    - The bench-scale system converted over 98% of the carbon in the slurry to energetic gases, including clean pressurized methane, hydrocarbons and carbon oxides in less than one minute, which is twice as fast as the target time.
2. No noticeable erosion, corrosion or deposition was observed in the test equipment.
3. Total suspended solids in the liquid effluent was less than 10%, supporting the feasibility of recycling liquids for slurry preparation after filtering to provide a "zero effluent" design. No toxic materials were produced that would limit disposal of the residue in a landfill.
4. A thermodynamic computer simulation model and a life cycle cost model were prepared and compared to an ASPEN simulation prepared for U.S Patent 5,280,701; however, there was insufficient funding in the current project to validate the models over a range of inputs, including the test data. Equilibrium compositions were assumed to be sufficiently

close to expected commercial operations to provide preliminary predictions of system performance. Results of the computer simulations included:

- Projected 62% thermal efficiency to electric power for the entire proposed hybrid plant. Projected efficiency for application to an existing steam power plant is over 50%.
- Projected capital costs of $1,100/kWh for a new hybrid plant, with projected cost of baseload power generation at $100/MWh.
- Projected capital costs of $500/kWh for retrofit to an existing GTCC plant, with projected cost of baseload power generation at $50/MWh.
- Retrofits for repowering existing boiler plants are competitive with GTCC plants burning natural gas at over $3.00/million Btu.

Conclusions

1. The test results support the continued investigation of composted municipal waste as an economical fuel source for GTCC and existing steam power plants.
2. We demonstrated that compost made from municipal solid wastes and sewage sludge can be made into slurry with 40 wt% solids, which significantly increases the range of applications, including the production of valuable byproducts, such as hydrogen. This mixture tended to clog in the ¼ inch preheater tube which was completely alleviated by changing to 3/8 inch tubing. This problem is not expected in larger tubes.
3. The project successfully demonstrated that the compost slurry can be used in a SCWG process to produce energetic gases and steam, including approximately 35% gaseous hydrocarbons and hydrogen, the largest fraction being methane. The remaining 65% of the carbon in the feed was converted mainly to CO_2 and a small amount of CO. The CO_2 can be separated for reduced emissions. It is unknown what effect compost grinding had on residence time for gasification. It is also unknown what impact scaling up the reactor tubes will have on the SCWG process.
4. Sufficient yield data was collected to determine gas composition, perform a carbon balance and perform a preliminary evaluation of recycling liquids after filtering for slurry preparation. While no corrosion, erosion or deposition was observed after running the tests, the tests conducted were not designed to accurately assess those effects over long-term testing.
5. Based on residence time and projected full scale reactor tubes, a standard module of 100 reactor tubes in a heat recovery steam generator (HRSG) per 25 MW turbine can consume an estimated 170 tons of composted municipal solid waste per day, reducing it to approximately 34 tons of inorganic residue.
6. The results of the preliminary computer simulation models are encouraging in terms of supporting an economic case for commercialization; however, the models include many assumptions that remain to be validated.

Benefits to California

This project contributed to the Public Interest Energy Research (PIER) program objective of reducing the cost of California electricity through the use of inexpensive biomass fuels. The project also contributed to the PIER objective of reducing environmental risk by diverting waste streams away from landfills.

Successful commercialization of SCWG technologies could promote business opportunities in several industries, including process development, waste disposal, electrical generation, pollution control and transportation fuels.

Recommendations

The next step is to assess the regime of slurry concentrations by conducting tests over the useful range using full-scale HRSG reactor tubes. Full-scale tubes are being installed in a new pilot plant under construction at General Atomics in San Diego. Test to determine the following:

1. Identify the optimum concentration of slurry that can be successfully gasified in full size reactor tubes,
2. Identify the optimum level of grinding required (if any) for trouble free gasification in full size reactor tubes,
3. Confirm slurry distribution in a 10-tube inlet manifold for scaleup to a commercial plant,
4. Confirm that the energy balance for SCWG does not change as a result of using full size reactor tubes,
5. Evaluate the longer-term potential for corrosion, erosion or deposition,
6. Test condensate for yield and quality and cleaning methods for recycle to slurry preparation,
7. Test ash for beneficial use or land filling,
8. Test mild operating conditions for byproduct yields and quality, including liquid hydrocarbons and carbon,
9. Refine computer models and economic feasibility analyses for retrofit to existing gas turbines and boilers, and
10. Collect and test fuel gases for combustibility in existing gas turbines, fuel cells and boilers.

Introduction

The purpose of this project was to research the technical and economic feasibility of a supercritical water gasification (SCWG) process to convert compost made from municipal solid wastes and sewage sludge to clean energetic gases in an anaerobic environment. The goal is to reduce the fuel costs of gas turbine combined cycle (GTCC) power plants and to improve both efficiency and environmental performance of existing steam power plants. Based on the use of renewable fuels, this project primarily supports the Renewable Energy Technologies PIER subject area.

The specific SCWG process investigated in this project was the patented Vapor Transmission Cycle (VTC) in which a slurry mixture is pumped under high pressure and temperature through specially designed heat recovery steam generator (HRSG) tubes situated in the exhaust of a gas turbine such that SCWG parameters are achieved within the tubes. Physical testing was conducted in an existing bench scale system at General Atomics (GA) facilities in San Diego, coordinated by the Principal Investigator.

A slurry mixture of composted municipal wastes and sewage sludge, generated from a conventional digester, was used in the bench scale system to establish the yields of generated gases and liquid effluent. The data generated was then used to update the computer modeling, life cycle cost analysis, and comparison of the proposed process with published information from competing processes. Based on an analysis of the data, this project was successful in establishing concept feasibility with sufficient confidence to warrant follow-on testing of the process in an advanced continuous-flow pilot plant. Successful operation of a continuous-flow plant would provide sufficient support for commercialization.

Project Objectives included:

1. Determine the feasibility of using SCWG to gasify composted municipal solid waste/sludge, consisting of at least 23 wt% solids, with a minimum 96% conversion of carbon to gas.
2. Verify through visual inspection that no significant erosion, corrosion and deposition occurred inside the bench-scale system.
3. Assess the feasibility of recycling resulting liquids for “zero effluent” design.
4. Update and validate simplified thermodynamic computer simulation and a life cycle cost models that can be used to predict system performance with various fuels.

The patented process under study, described in U.S. Patents 5,280,701 & 5,339,621, is named the Vapor Transmission Cycle, (VTC), and incorporates the SCWG process. In the Vapor Transmission Cycle, HRSG tubes are modified to distribute slurry and transfer sufficient heat to meet SCWG heat requirements without oxygen addition, including raising the temperature of the slurry to saturation, vaporization, and chemical reactions. The tubes are designed to accept slurry solutions containing minerals and metals without corrosion and deposition on heat transfer surfaces, up to and including the supercritical conditions of water, above 221 bar (3205 psia) and 374 ^{o}C (705 ^{o}F). The tubes must be of sufficient length to provide adequate residence time and surface area to allow reactions to occur. A commercial method of fluidized particle scrubbing is used to improve heat transfer and prevent corrosion and deposition on heat transfer surfaces.

The HRSG reactor tubes are designed to generate clean fuel gases, CO_2 and steam for GTCC power plants by feeding water slurries or emulsions above about 20% organics, including heavy oil, coal fines, bitumen, tar sands, biomass, compost, crumb rubber and sludges.

Supercritical steam generators have been developed to increase the efficiency of coal fired power generation up to 40%. Steam is produced in tubes by a smooth transition to vapor at less than 1/10 of the density and more than ten times the velocity of the feedwater. Figure 1 illustrates the temperature and density relationships of water at selected pressures.

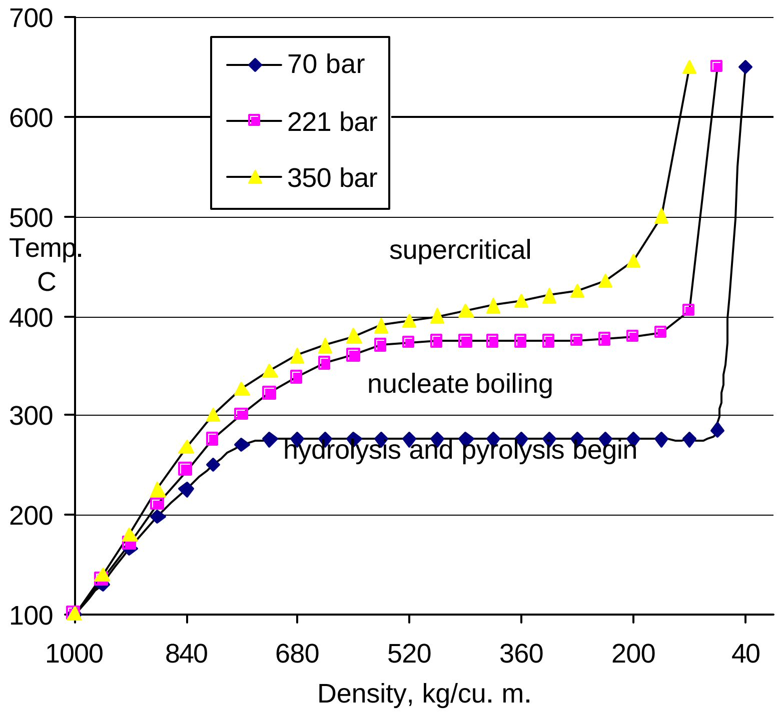

Fig. 1 Temperature vs. density for water at various pressures

The HRSG tubes depend on external heat transfer through a containment surface to a pressurized fluid that can contain a solvent (water), dissolved or emulsified materials, or slurry. The water can contain organic materials, granular media, catalysts, and pH control reagents. Inorganic materials can include sulfur, chlorine, fuel nitrogen, alkali metals, ash, vanadium and other metals. When chlorine is present it can react to form hydrochloric acid, which would preclude the use of low-alloy system components in high temperature areas.

The qualities of many supercritical solvents, including hydrocarbons and carbon dioxide (above 31 C and 74 bar) are well known, cost-effective, and in commercial use for cleaning and selective separations of organics. Water, the most important solvent in nature, has fascinating properties as a reaction medium in its supercritical state, where it behaves very differently from water at standard conditions. Supercritical water, above 221 bar (3205 psia) and 374 C (705 F), dissolves organics and precipitates inorganic materials, as shown in Figure 2. The solvent advantages of inorganic supercritical fluid solvents (e.g., water and CO_2) over conventional organic solvents, and the application of supercritical fluids for complex matrix interactions have been reported (Hawthorne, 1994).

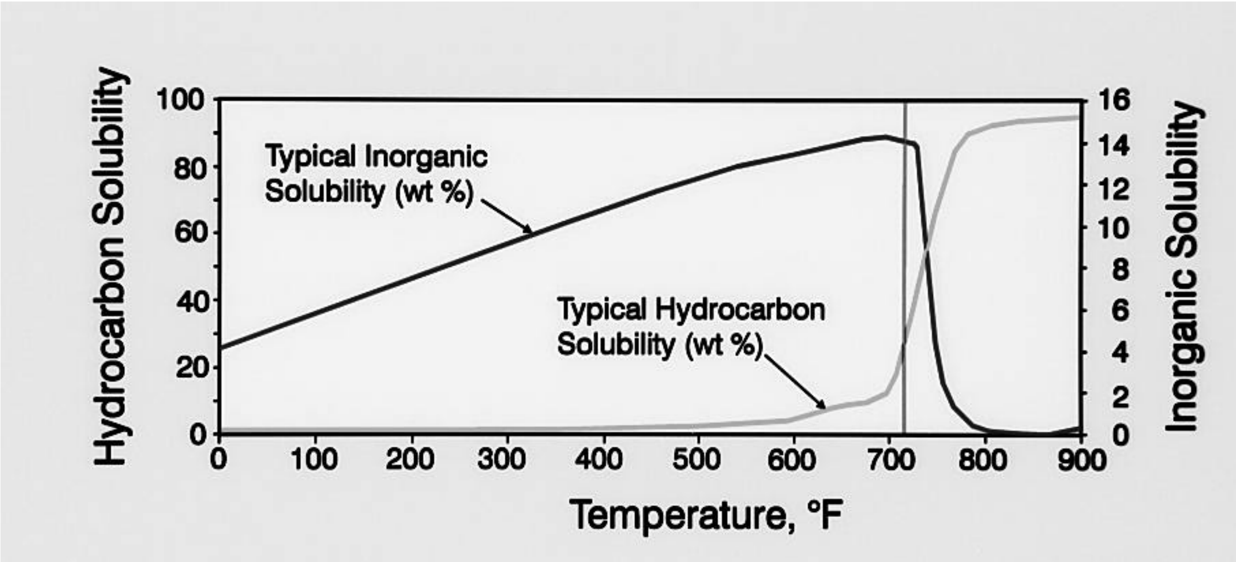

Fig. 2 Water Solvency at 221 bar (3205 psia)

The polarity and solvent qualities of water can be controlled by temperature and pressure. Most organic materials dissolve in all proportions in supercritical water. Unsaturated metal centers may be able to coordinate with organic target molecules, thereby catalyzing degradation of the targets in supercritical water (Sealock, 1996). In addition, the presence of a second solute such as carbon dioxide produced by these reactions may augment supercritical water solvency.

Regardless of its pressure, supercritical steam gasifies organic materials, forming highly combustible, lighter hydrocarbons, hydrogen, methane and carbon dioxide. Given sufficient residence time an analogous gasification of carbonaceous materials will occur using supercritical water (Modell, 1978.)

Formation of carbonaceous char from less reactive carbonaceous materials such as coal is favored by short residence time, large particle size, and subcritical conditions (GA, 1997). High-carbon char has been produced by subcritical and supercritical water (Hawthorne, 1990).

Supercritical water shows promise in catalytic partial reforming of slurries made from refuse derived fuel, waste plastics, coal fines, and coal water fuels (Shaw, 1991). Data shows that fuel nitrogen will be converted to nitrogen gas (Sealock, 1996). Inorganic materials, such as sulfur, chlorine, alkali metals, ash, vanadium and other metals can be separated and removed for recycle or disposal. Activated carbon has been proposed as a catalyst for the conversion of biomass to hydrogen and methane in supercritical water. Unconverted carbon can be sequestered in char for decreased carbon dioxide emissions, or burned with additional coal in existing combustors.

If salts are present in the feed, or formed during processing, they will precipitate from solution wherever local temperatures exceed the critical temperature. Unless these solids are effectively transported through the supercritical region and effectively removed from the process, accumulations will form and plug the reactor tubes. Use of a commercial method of fluidized particle scrubbing using absorbent media has been proposed to prevent fouling and enhance heat transfer. The media can also be inert particles added to the feed or naturally present in the feed.

A commercial once-through HRSG tube bundle is shown in Fig. 4 with the inlet header. The tubes can be serpentine with extended external surface and over 100 ft. in length. Residence time can be controlled by the flow rate and the rate of heat transfer.

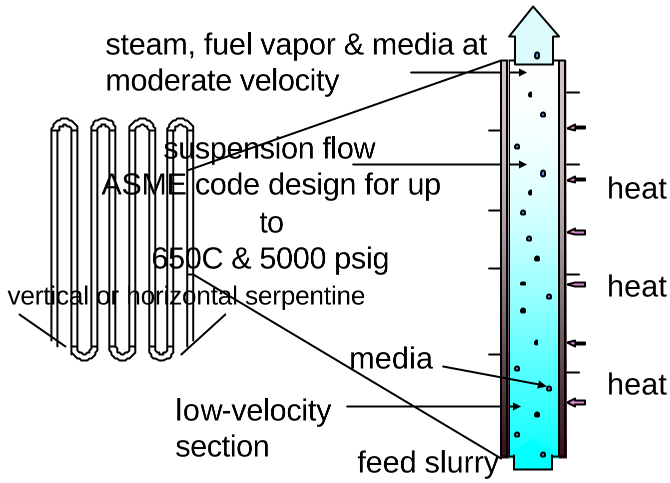

Fig. 3 Fluidized Transport Reactor Tube

Fig. 4 IST Once-Through Tube Bundle

Courtesy of Innovative Steam Technologies

Salts can be transported through the HRSG tubes by precipitating them on solid granular media in the system. Deposits can be minimized and heat transfer improved due to media impingement on the tube surface. Erosion can be minimized by using erosion and corrosion-resistant materials such as Alloy 800H in the heat transfer surface and by controlling slurry velocity.

Subsequent sections of this report describe the project approach, outcomes, conclusions, recommendations, and development stage assessment. Supplementary material includes a glossary, references and appendices. Appendix I is the General Atomics Test Report, and Appendix II contains additional information on SCWG and a description of the VTC.

Project Approach

In order to accomplish the Project Objectives, the project was organized into the following tasks:

Task 1 Bench-Scale Tests

General Atomics performed task 1 under the direction of Mr. Radon Tolman, Principal Investigator. The primary goal of Task 1 was to develop yield and quality data for applying supercritical conditions to convert compost to clean fuels on the bench-scale system. The results of these tests were used in the simulation modeling and cost and performance analysis of Tasks 3 and 4. In addition, the data will be used for the development and operation of the pilot plant.

The initial bench-scale equipment contained ¼ inch tubes with an inside diameter of .2 inches. These proved to be prone to plugging by large particles in the compost feed. The feed was ground to reduce particle size below about 500 microns. The small tubes in the bench-scale equipment were replaced by 3/8 inch tubes and some equipment was changed to lab-scale to more closely control the system. Details are included in Appendix I.

Task 2 Ultimate Analyses

Task 2 was performed by GA under the direction of the Principal Investigator. Analysis of the feed sample was to include proximate and ultimate analyses. Products were to be weighed. Gas and liquid products were to be analyzed to determine fuel values and to estimate further treatment that may be required to meet requirements for their use as fuels. Gases were to be analyzed for hydrogen, methane, light hydrocarbons, carbon dioxide, carbon monoxide and hydrogen sulfide. Liquid product were to be extracted with solvent to remove water and analyzed in a gas chromatograph for hydrocarbons, chlorine, sulfur, alkali metals, and total organic carbon.

Task 3 Incorporate Data in Simulation Model

Task 3 was performed by Dr. Jerry Parkinson, consultant, under the direction of the Principal Investigator. The process model was developed using existing subroutines where possible. The computer model is particularly useful for system optimization and will enable performance of economic evaluations based on both capital and operating costs associated with changes in operating conditions and/or system configuration. It will also enable determining the impacts of scale changes to both the design and the life-cycle costs of the process. The computer modeling effort began at the same time as the bench-scale experimentation and proceeded in cooperation with that work. This coordination was vital to ensure that all data necessary for the development of the simulation model are collected during the experimental runs. Other potential benefits of task coordination included use of the developing computer model to help validate the data collected (mass and energy balances, etc.), and to run sensitivity analyses for determining the most critical control parameters, which could help focus other work. The process simulation model will be continually refined and modified through input of pilot plant data.

Task 4 Feasibility Analyses

Task 4 was performed by the Principal Investigator with input from the consultant. Cost and performance analyses were to be prepared using the methods of the National Renewable Energy Laboratory, Golden, CO (Craig, 1996). The purpose of that study was to determine the efficiency and cost of electricity for IGCC systems incorporating biomass gasification technologies. The systems examined incorporate state-of-the-art commercially available aero-derivative and utility gas turbine technology and modern heat recovery steam cycle technology. It was clear from this study that even the most promising electricity costs from biomass were higher than currently quoted avoided costs and new high-efficiency natural gas fired combined cycle systems.

Preliminary capital and operating cost estimates were prepared for each alternative. Spreadsheets were prepared for comparing present values of the alternatives. The resulting comparisons indicate the commercial potential of the VTC system compared with published information for competitive systems, and define areas for continued and focused research in a pilot plant.

Task 5 Prepare Final Report

Task 5 was performed by the Principal Investigator. The results of Tasks 1 through 4 are presented in this report. Sensitivity analyses were to be prepared for variations in capital and operating costs associated with the uncertainties of the preliminary estimates and the risks associated with further research and development. A preliminary cost estimate and schedule for the pilot plant are included in this report, and incorporated in cumulative discounted cash flow projections for evaluation of the required research and development investments.

Details of the steps taken to achieve the stated goals, types of analyses performed on the data collected, and findings are included in the Appendices. Some conclusions from the testing are also included in Appendix I. Additional conclusions have resulted from the preliminary process modeling and feasibility analyses.

Project Outcomes

Use of SCWG to gasify composted municipal solid waste/sludge is feasible by a wide margin:

- We produced pumpable slurry mixture containing 40 wt% solids, exceeding the target goal by 74%.
- The bench-scale system converted over 98% of the carbon in the slurry to energetic gases and steam, including clean pressurized methane, hydrocarbons and carbon oxides in less than one minute, which is twice as fast as the target time.

The ultimate analysis for the compost used in the project was based on Bedminster data shown in Table 1. This analysis was assumed to be sufficiently representative of the cured compost before slurry preparation. Preparation of the slurry feed required grinding of the compost material to reduce particle size to avoid clogging in the tubes in the lab-scale system (See Appendix I). Testing is planned in a pilot plant to identify the optimum level of grinding required (if any) for trouble-free gasification.

Table 1. Ultimate Compost Analysis

Component	Weight Percent
Moisture, as received	18.7
Carbon	34.1
Hydrogen	3.3
Oxygen	19.2
Nitrogen	0.7
Sulfur	0.2
Chlorine	0.4
Ash	23.4

The gross heating value of the compost was calculated using Dulong's formula:

$$\textbf{Higher Heating Value (HHV in Btu/lb)} = 14096*C + 61{,}031*(H - O/8) + 3{,}984*S,$$

Where C,H,O and S are the weight fractions of carbon, hydrogen, oxygen and sulfur in the sample. The HHV for the dry compost was calculated as about 6,600 Btu/lb. The HHV of the 40% solids slurry was then about 2,640 Btu/lb. See Appendix II for a discussion of lower heating value (LHV) and the exergy of slurries.

A summary of test results follows:

- Through experimentation pumpable biomass slurry mixtures containing 40 wt.% solids were achieved which exceeded the target goal of 23 wt.% solids.
- The lab-scale heat recovery steam generator converted 98% of the carbon in the slurry to gases.
- Gases produced from composted sewage sludge and municipal waste:
  - 8-11% H_2
  - 16-17% CH_4
  - 7-12% CO

- 56% CO_2
- 6% Other

- The high concentration of CO_2 is a direct result of high oxygen content in the feed. All of the pressurized gases from SCWG can be used to produce electric power in the VTC expander turbine. However, excess CO_2 and steam may interfere with combustibility in the gas turbine combustor. This potential problem will be addressed in the pilot plant testing stage of development.

- Liquid effluent analysis:
  - 1350-2630 mg/kg total organic carbon
  - 7.66-7.81 pH
  - <0.01 mg/kg Cr
  - <0.04 mg/kg Ni
  - <1.52 mg/kg Fe
  - 93,000 mg/kg total suspended solids

- Total suspended solids in the liquid effluent was less than 10%, supporting the feasibility of recycling liquids for slurry preparation after filtering to provide zero liquid effluents. No toxic materials were produced that would limit disposal of the residue in a landfill.

- No noticeable erosion, corrosion or deposition was observed in the test equipment.

- A thermodynamic computer simulation model and a life cycle cost model were prepared and compared to an ASPEN simulation prepared for U.S Patent 5,280,701; however, there was insufficient funding in the current project to validate the models over a range of inputs, including the test data. Equilibrium compositions were assumed to be sufficiently close to expected commercial operations to provide preliminary predictions of system performance. Results of the computer simulations included:
  - Projected 62% thermal efficiency to electric power for a hybrid plant using a solid oxide fuel cell. Projected efficiency for application to an existing steam power plant is over 50%.
  - Projected capital costs of $1,100/kWh for a new hybrid plant, with projected cost of baseload power generation at $100/MWh.
  - Projected capital costs of $500/kWh for retrofit to an existing GTCC plant, with projected cost of baseload power generation at $50/MWh.
  - Retrofits for repowering existing boiler plants are competitive with GTCC plants burning natural gas at over $3.00/million Btu.

A computer-based process simulation model was prepared for a net 156 MW hybrid version of the VTC that includes material and energy balances. The heat and mass balance data were adjusted for 50 MW total output. Results predicted 62% HHV thermal efficiency to electric power using a supercritical steam turbine, a solid oxide fuel cell and a commercial gas turbine. The improved system appears to be patentable (See Appendix II).

Conclusions and Recommendations

This project resulted in the following conclusions:

- The test results support the continued investigation of composted municipal waste as an economical fuel source for GTCC and existing steam power plants.
- We demonstrated that compost made from municipal solid wastes and sewage sludge can be made into a slurry with 40 wt% solids, which significantly increases the range of applications, including the production of valuable byproducts, such as hydrogen. This mixture tended to clog in the ¼ inch preheater tube which was completely alleviated by changing to 3/8 inch tubing. This problem is not expected in larger tubes.
- The project successfully demonstrated that the compost slurry can be used in a SCWG process to produce energetic gases and steam, including approximately 35% gaseous hydrocarbons and hydrogen, the largest fraction being methane. The remaining 65% of the carbon in the feed was converted mainly to CO_2 and a small amount of CO. The CO_2 can be separated for reduced emissions. It is unknown what effect compost grinding had on residence time for gasification. It is also unknown what impact scaling up the reactor tubes will have on the SCWG process.
- Sufficient yield data was collected to determine gas composition, perform a carbon balance and perform a preliminary evaluation of recycling liquids after filtering for slurry preparation. While no corrosion, erosion or deposition was observed after running the tests, the tests conducted were not designed to fully assess those effects over the long-term under standard operating conditions.
- Environmentally, based on residence time and projected full scale HRSG tubes, a standard module of 100 HRSG tubes per 25 MW turbine can consume an estimated 170 tons of composted municipal solid waste per day, reducing it to approximately 34 tons of inorganic material.
- The results of the computer simulation models are encouraging in terms of supporting an economic case for commercialization; however, the models still include many assumptions that remain to be validated.

The next step is to assess the regime of slurry concentrations by conducting tests over the useful range using full-scale HRSG reactor tubes. The logical test bed would be the new SCWG research pilot plant being constructed at General Atomics in San Diego that is designed to test a wide range of SCWG applications. Additional funding is needed to conduct tests to determine the following:

- Identify the optimum concentration of slurry that can be successfully gasified in full size reactor tubes,
- Identify the optimum level of grinding required (if any) for trouble free gasification in full size reactor tubes,
- Confirm slurry distribution in a 10-tube inlet manifold for scaleup to a commercial plant,
- Confirm that the energy balance for SCWG is the same using full size reactor tubes,
- Evaluate the longer-term potential for corrosion, erosion or deposition,
- Test condensate for yield and quality and cleaning methods for recycle to slurry preparation,
- Test ash for beneficial use or land filling,
- Test mild operating conditions for byproduct yields and quality, including liquid hydrocarbons and carbon,

- Refine computer models and economic feasibility analyses for retrofit to existing gas turbines and boilers, and
- Collect and test fuel gases for combustibility in existing gas turbines, fuel cells and boilers.

By establishing the technical feasibility of the proposed SCWG concept, the project moves one step closer to making a significant contribution to the Public Interest Energy Research (PIER) program objective of improving energy cost of California electricity through the use of inexpensive biomass fuels. The project also has the potential to contribute to the PIER objective of mitigating environmental risks, including reducing emission of greenhouse gases and ground water contamination by removing biomass materials from the landfill and by diverting waste streams away from landfills.

The data generated in this project resulted in a projected increase in system efficiency of 10% for an existing steam power plant retrofitted with this technology. This increase derives from the current efficiencies of about 40% being improved to over 50% with this technology. Further, an increase in plant biomass consumption capacity of 220% was obtained over the previous best estimates. This percentage is based on the demonstrated increased percentage of solids in the slurry and shorter residence time required in the HRST tubes.

California is currently generating about 575 Mw from biomass sources (cited from California Biomass Energy Alliance). These plants use forestry, agricultural and urban wood wastes for fuel. With this technology we can add composted MSW, sewage sludge and green yard wastes. The city of San Diego alone generates 200,000 tons of these materials yearly. It is estimated that the major urban areas of California generate sufficient MSW and sewage sludge to support Ten 50 MW combined cycle power plants of the type proposed for a total capacity of 500 MWs. Requirements to increase the diversion of landfill waste streams and the increasing costs of natural gas further reduces the risks associated with commercialization. The lifecycle cost analysis targets fuel cost of the processed compost at about $1.00/Mbtu. This is based on the assumption that the tipping fees cover the majority of the cost of processing the biomass into compost.

Assuming the ten 50 MW combined cycle power plants were built and used for base load generation at 80% availability (7000 hours/year), they will produce 3,500,000 Mwh of electricity per year. Under current conditions this power could be sold on a long term contract at 7 to 8 cents/Kwh, resulting in revenues of $280,000,000 per year. Consider that the fuel cost savings of displacing natural gas at $5.00 Mbtu in this analysis results in fuel cost savings of about $100,000,000 / year.

Development Stage Assessment

Table 2 is a bar chart table describing the overall development effort in terms of the EISG Stages and Gates process.

Table 2. Project Development Stage Activity Matrix

Stages / Activity	1 Idea Generation	2 Technical & Market Analysis	3 Research	4 Technology Develop-ment	5 Product Develop-ment	6 Demon-stration	7 Market Transfor-mation	8 Commer-cialization
Marketing								
Engineering / Technical								
Legal/ Contractual								
Risk Assess/ Quality Plans								
Strategic								
Production. Readiness/								
Public Benefits/ Cost								

- Marketing
  Graduate students at the University of Colorado Business School prepared a preliminary Business Plan. This preliminary Plan is outdated and needs to be changed with a new title and improved schedules and costs to be determined in the proposed Stage 4 technology development project. Customer needs should be clarified as part of this process, including estimates of market potential for various applications of the technology. Potential commercializers should be contacted and interviewed for the Business Plan to provide feedback from existing customers as well as to identify additional customers and stakeholders.

- Engineering/Technical
  Performance goals have been set, as outlined in this report, including over 50% thermal efficiency for retrofit projects, power costs below $0.05/kWh, fuel cost reductions, minimum emissions and zero liquid effluents. A technical analysis should be prepared using a peer review process approved by the Commission. The product has met or exceeded the technical goals set for the project in Stage 3 and met the feasibility criteria.

  There is justification to proceed with the proposed Stage 4 development project with pilot plant testing before solving the remaining technical problems. The pilot plant is the only source of sufficient equipment, instrumentation, capacity and capabilities to solve the remaining technical problems. A Test Plan for the pilot plant and subsequent field experiments should be developed to direct data acquisition and analysis that support the proposed process and economic models.

  - Legal/Contractual
    U.S. Patents 5,280,701 and 5,339,621 have already been issued. Development of additional intellectual property, including improvements and information related to specific

applications is anticipated. Proprietary information, including intellectual property, will be protected in accordance with best business practices and Commission requirements. No other legal patents issues have arisen at this time.

Identified commercializers will be asked to submit existing and projected sales data as part of the process for selecting a commercializer for this technology.

- Risk Assessment/Quality Plans
  A Quality Plan needs to be developed that meets ISO 9004 Quality Management and ISO 9001 Quality Assurance criteria. The Quality Plan will specify quality control criteria, including technical performance, safety and environmental performance, in accordance with ASME, AWS, ASTM, IEEE standards, California and federal regulations. Selected elements of the Quality Plan will minimize risks by applying risk reduction techniques with safety analysis methods.

  Environmental and safety issues include measurement and prediction of any emissions based on pilot plant results, continuous emissions monitoring, zero liquid effluents, residue disposal and licensing. These issues will be resolved during the proposed Stage 4 development project so that Gate 4 criteria will be met.

  A life cycle analysis is proposed to be performed early in the pilot plant step of Stage 4 development to support life cycle cost analyses and predictive maintenance costs for the Business Plan. No new risks have been identified at this time. Any new risks that result from the proposed Stage 4 pilot plant testing will be identified and reported in accordance with Commission requirements in close collaboration with PIER staff.

- Strategic
  Development of the technology has been linked to PIER policy objectives. This project does not appear to impact other PIER projects at this time. This project is not critically dependent on other projects under development within PIER or elsewhere.

- Production Readiness
  A research and development collaborator has been identified in General Atomics in San Diego. Top candidates for commercializing partner remain to be identified and interviewed in support of product marketing and the revised Business Plan to fulfill legal and contractual requirements described above. The selected commercialization partner should submit evidence of a firm commitment based on successful completion of Stage 4 tasks and meeting the criteria for Gate 4 product development and field testing in Stage 5.

- Public Benefits/Costs
  The empirical data generated in this project resulted in a significant increase to the calculated California public benefit-cost ratio. Project results support continued concept development for retrofits to existing natural gas fired boilers and combined cycle plants. The benefits to be derived from substituting biomass fuels for higher-cost fuels, including more expensive natural gas has improved since this project was completed.

References

1. Hawthorne, S. B.; Yang, Y.; Miller, D.J. "Extraction of Organic Pollutants from Environmental Solids with Sub- and Supercritical Water," *Anal. Chem.* **1994**, 77, 18

2. Modell, M., "Gasification Process," U.S. Patent 4,113,446, **1978**

3. Hawthorne, S. B., "Analytical-Scale Supercritical Fluid Extraction," *Anal. Chem.* **1990**, 62, 633A-642A

4. Shaw, R. W.; Brill, T. B.; Clifford, A. A.; Eckert, C. A.; Franck, E.U. Supercritical Water - A medium for Chemistry, *Chemical and Engineering News* **1991**, Dec. 26

5. Sealock, L.J., et al, "Chemical Processing in High-Pressure Aqueous Environments-5," New Processing Concepts, *Ind. Eng. Chem. Res.*, **1996**, 35, 4111-4118

39037-902/A

APPENDIX I

SUPERCRITICAL WATER GASIFICATION OF BIOMASS/RDF COMPOST

FINAL REPORT
EISG Grant Number 51233A/99-01-24

PROJECT 39037

General Atomics
3550 General Atomics Court
San Diego, CA 92121-1194

September 1999 - February 2000

GENERAL ATOMICS

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

A supercritical water gasification (SCWG) system for biomass/RDF compost is being developed to provide fuel gases for power production. Bench-scale tests were performed to provide data on supercritical water gasification of biomass/RDF compost. Important issues for supercritical water gasification of biomass/RDF compost include:

- slurry pumping
- product spectrum and conversion versus operating temperature and pressure
- char formation
- corrosion
- solids handling / salts transport

These tests focused on the pumping and conversion and product spectrum versus operating temperature, but operation of the system also provided information about char formation, corrosion, and salts/solids handling as well. The primary objective was to determine the product spectrum and conversion efficiency for gasification of biomass/RDF compost at 3400 psig over range of temperatures from 500°C to 650°C. In addition, the ability to pump the biomass/RDF compost and move solids through the system was qualitatively assessed. None of the planned tests were planned to be long enough to generate quantitative corrosion data. However the degree of corrosion was qualitatively assessed.

The Test Plan (Ref. 1) identified objectives for the tests. The objectives were met with the following results from testing:

- Stable, size-reduced slurries containing up to 40 wt% compost were prepared and pumped through the gasification system
- High gasification efficiency (98%) was achieved with little char or tar formation
- No corrosion was observed in the gasification system

1. INTRODUCTION

The purpose of this project is to convert the latent fuel values in two large volume California waste streams (sewage sludge and municipal solid waste) to a usable form: a gaseous fuel that may be used in a variety of power cycles, including:

- stationary sources, such as gas turbines and fuel cells, and
- mobile sources, by separating the hydrogen produced.

The purpose of this report is to convey results of bench-scale testing of supercritical water gasification (SCWG) of slurries of composted sewage sludge and municipal solid wastes. These wastes were received as composted solids. They were mixed with water to form stable, high-density slurries, which were then pumped into the SCWG reactor at pressures exceeding 3500 psia. In the SCWG reactor, the compost slurries were gasified at >600°C to form mixtures of combustible gases, including CO, CH_4 and H_2. These gases, along with the carbonized compost, were then reduced to atmospheric pressure to allow sampling of the gases and the remaining slurry for chemical analysis.

2. DISCUSSION

The project consisted of two distinct phases. The first phase was development of a feed preparation and pumping method. The second phase was laboratory-scale SCWG of the feed material. The results of testing during each of these phases are summarized in Sections 2.1 and 2.2.

2.1. COMPOST PUMPING METHOD DEVELOPMENT

2.1.1. Test Summary

Supercritical water gasification requires a feed pressure of greater than 3200 psig. Economical operation dictates the need for continuous feed of the material. The first objective of the project was to develop a reliable feeding method for continuous feed of compost at 3400 psig. The basic approach was to slurry the compost and feed it through a high-pressure pump. The initial goal was to achieve reliable pumping with a 23 wt% solids feed. Higher concentrations are generally required to minimize the heat required to evaporate excess water for energy recovery.

The compost feed preparation and pumping method produced 40 wt% dry solids slurries, which is nearly double the project goal of 23 wt% dry solids. The method is readily scalable. The slurry was easily pumped. GA has demonstrated this feed pump at larger scale with other slurries, and based on the operational results, feeding the compost slurry at larger scales should not pose any significant problems.

2.1.2. Narrative Test Description

The as-received compost was 81.3 wt% solids. Water was added to dilute the compost to 50 wt% solids. The resultant mixture still appeared dry. There was no apparent liquid or slurry phase. Further dilution to 40 wt% produced a thick slurry which could likely be pumped. Thus, 40 wt% solids was chosen as the new target for the feed concentration. Figure 1 presents a photograph of the slurry.

Fig. 1. Forty weight percent dry solids slurry of the as-received compost

The small size of the test equipment placed additional constraints because the compost had to be pumped through small diameter, ~0.18" ID, tubing. Most of the material in the compost was too big to flow through such small tubing, so size reduction was required. Four methods of size reduction were attempted.

The first attempt at comminuting the dry compost was with a food processor that had been used to successfully prepare other slurry. The material was not effectively size reduced, so a coffee grinder was used as an alternative. Good size reduction was attained with the coffee grinder, but unfortunately caking of the material made the process very slow. A heat gun was used to remove approximately 6 wt% of the water in the as-received compost. This improved the speed of the grinding operation by preventing some of the caking. The material was comminuted to 500 μm or less.

The dry ground compost was mixed with water and water containing a polymer thickener. The thickener was one that had been used to improve the stability of other slurries for feed to supercritical water oxidation systems (by preventing settling in the feed lines or pump). In both cases, the material appeared "dry" after dilution to 50 wt% solids, with no apparent liquid or slurry phase. Further dilution to 40 wt% solids yielded a thick slurry similar to the 40 wt% slurry of the as-received material. In both cases, the slurry appeared to be stable and adequate for pumping.

A great deal of effort was required to prepare the size-reduced compost via dry grinding. Therefore, other methods were tested. The selected approach enabled successful production of 40 wt% size-reduced slurries with very little effort. Figure 2 presents a photograph of the slurry produced with this method.

Fig. 2. Forty-weight percent dry solids slurry used for all SCWG tests.

The 40 wt% slurry produced was then tested in a proprietary high pressure pump to verify that it could be reliably pumped to 3400 psig. The slurry readily pumped at 3400 psig. Thus, the feed method selected was: (1) slurry preparation to attain a 40 wt% slurry, and (2) transferring the slurry to a high pressure pump for feed to the supercritical water gasification system.

2.2. SUPERCRITICAL WATER GASIFICATION

2.2.1. Test Summary

A small supercritical water gasification system was constructed and installed in a laboratory hood. Figure 3 presents the P&ID for this system. Figure 4 presents a photograph of the installed system. Table 1 summaries the tests performed. There were a number of difficulties associated with handling solids in such a small system. The approaches that GA has demonstrated in larger systems do not readily translate to very small systems such as this laboratory-scale unit. However, the problems were overcome such that proof-of-principle could be demonstrated for the compost slurry feed.

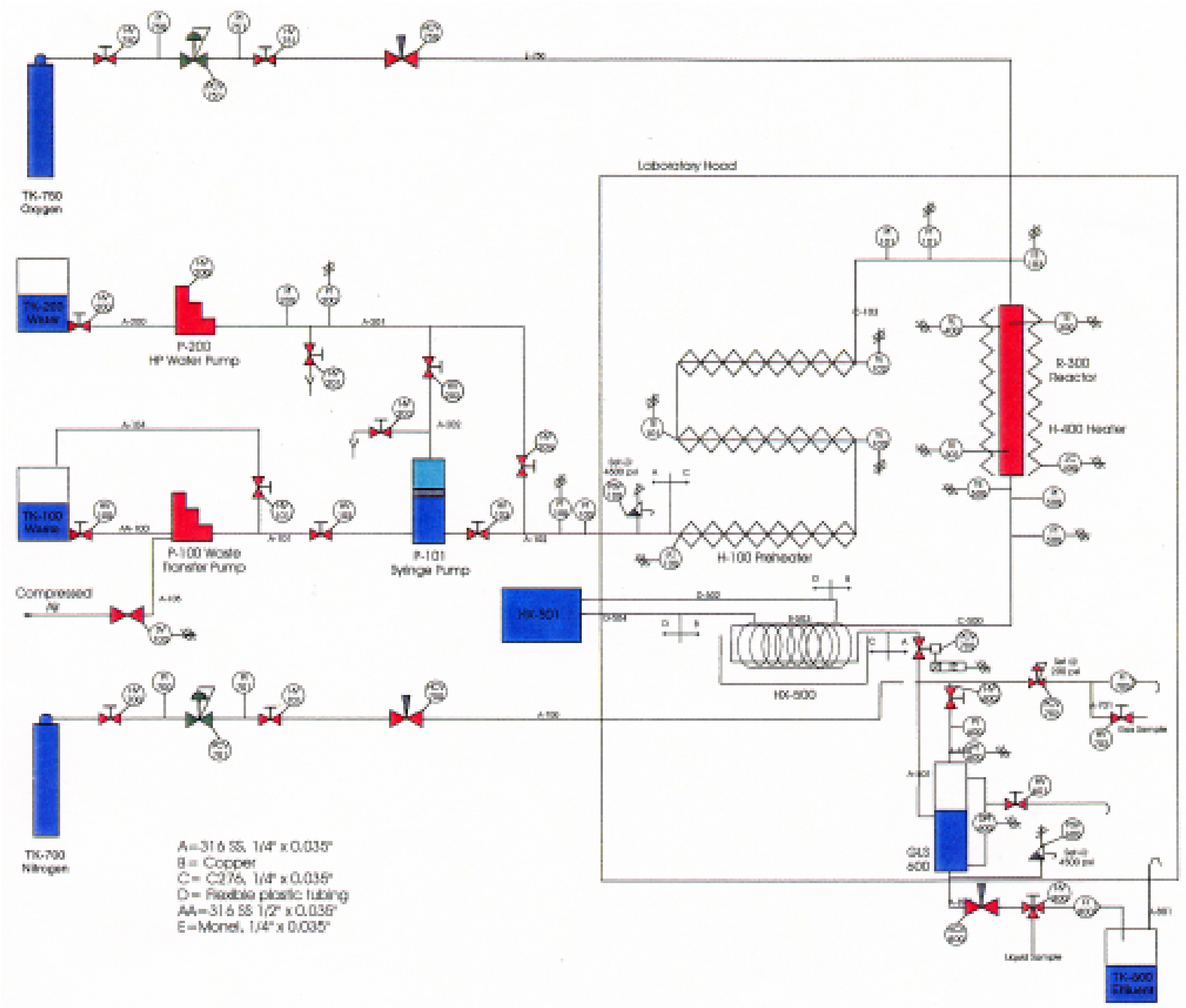

Fig. 3. Laboratory-scale SCWG system Piping and Instrumentation Diagram

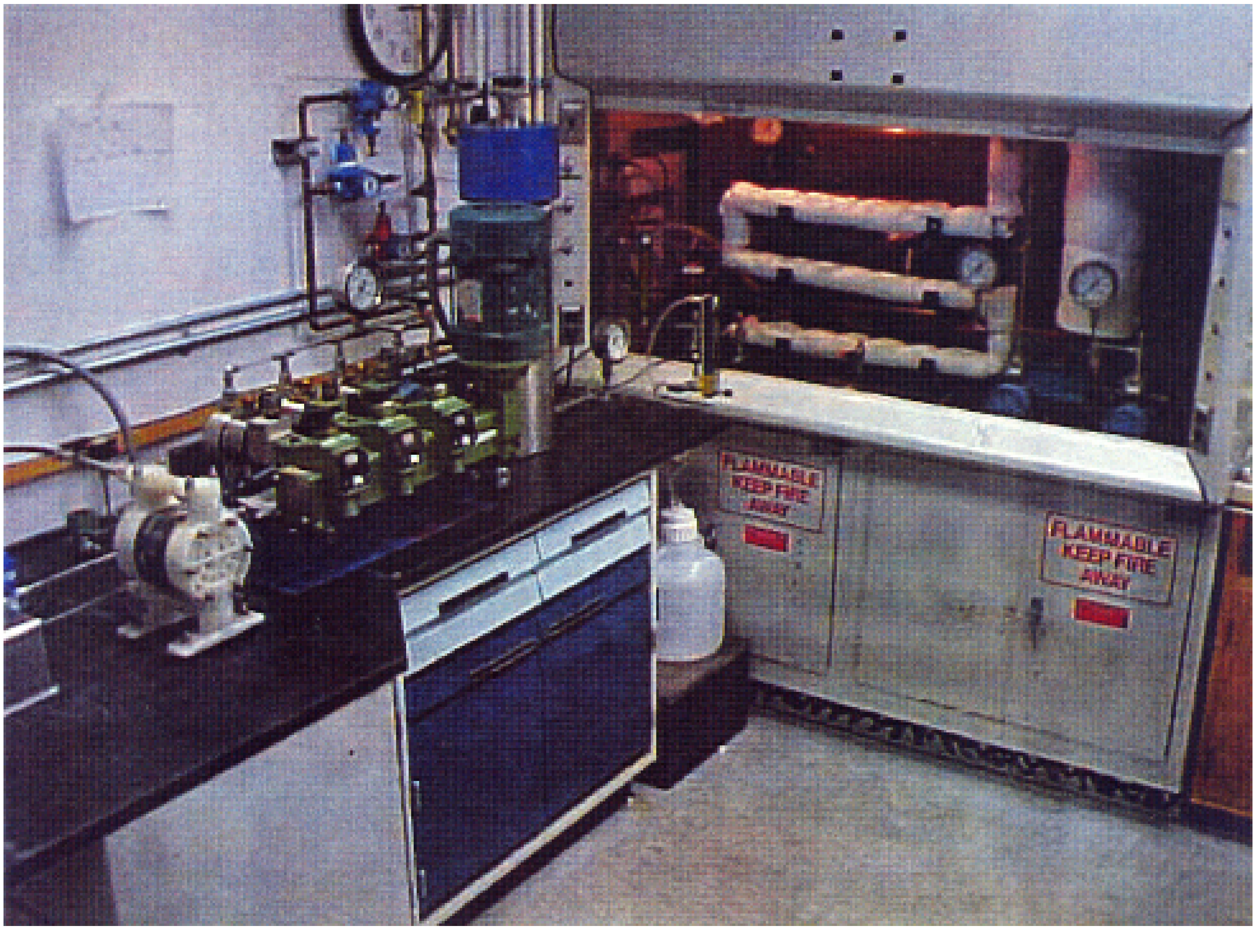

Fig. 4. Installed laboratory-scale SCWG system.

All of the major challenges were answered positively:

- A scalable method was developed to prepare size-reduced slurries
- Pumping of the slurry was demonstrated
- Operation without plugging the preheater, heat exchanger, or reactor was demonstrated
- No corrosion was observed
- Little char or tar formation was observed
- High gasification efficiency was achieved

The compost was successfully pumped, preheated, and gasified in the reactor. Approximately 98% of the carbon in the feed was gasified based on TOC in the effluent compared to the feed. The conversion efficiency could likely be improved by adjusting the residence time and temperature, and by operation in a larger system with better mixing in the reactor. There were no problems with plugging of the reactor or preheater provided flow passages of at least 0.18" were maintained. There was no observable corrosion of the reactor, preheater, or heat exchanger. There was very little char or tar formation, and the solids in the effluent corresponded well to the ash content of the feed material. Based on feed analyses, 11.5 wt% of the slurry was expected to remain as ash and ~10 wt% solid ash measured in the effluent.

The ash (23.4 wt% of the as-received compost and 11.5 wt% of the feed slurry) eventually plugged the effluent lines in all tests. Typically the plugs started at pinch points such as an internal thermocouple or the entrance to a flow valve. In a larger-scale system, the ash would not cause this type of plugging problem. The solids accumulation was primarily in the pressure control and effluent system. This caused pressure fluctuations, which in turn drove temperature fluctuations. Figure 5 presents a typical pressure and temperature plot for the tests.

Test Data during Compost Processing

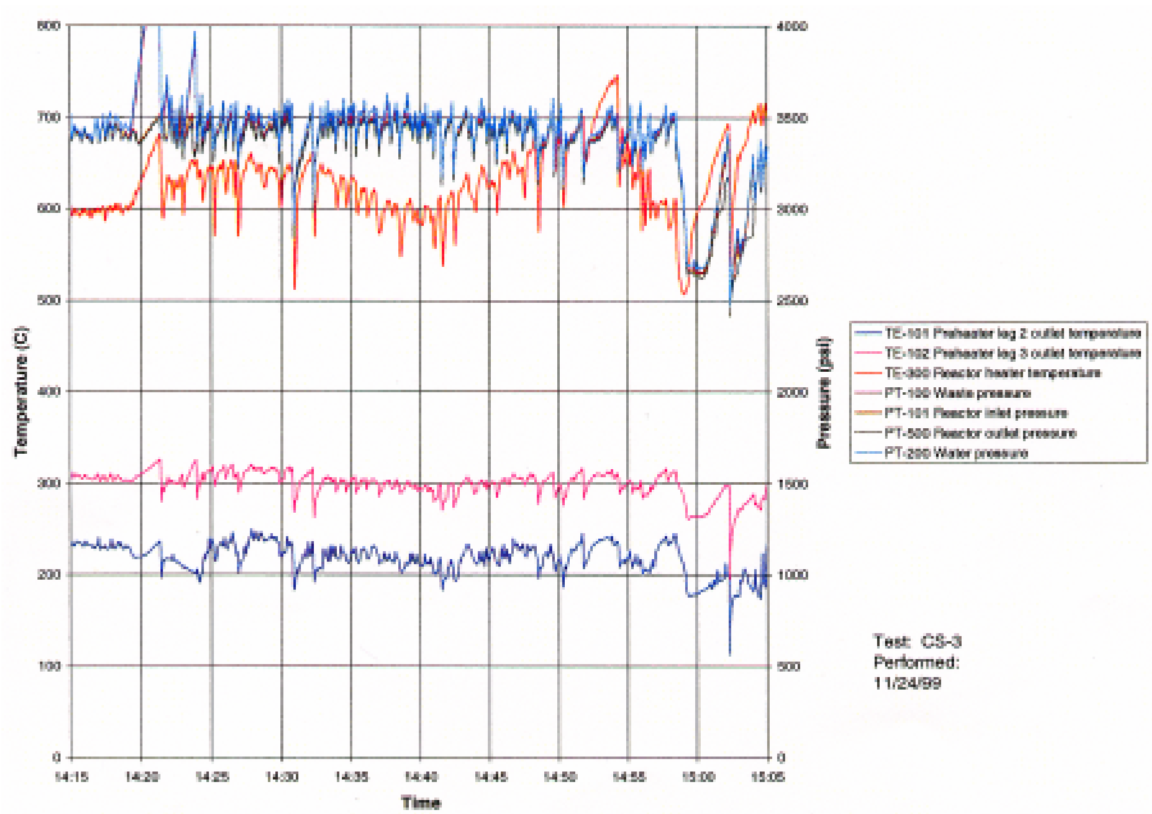

Fig. 5. Temperature and pressure curves for test CS-3

Gas analyses were obtained for two of the tests, CS-3 and CS-5. In both cases there was a substantial amount of CO and hydrocarbons other than methane. This indicates that additional time or higher temperature is required to drive the gasification toward equilibrium. In both cases, there was a substantial amount of CO_2 dissolved in the liquid phase that slowly percolated out. More of the CO_2 was found in the gas phase in CS-5. This occurred because the gas sample was taken shortly after the test for CS-3, whereas the gas sample was taken after the effluent equilibrated at a lower pressure over the weekend for CS-5. Approximately 65% of the carbon in the feed was converted to CO_2 or CO (which can be shifted to CO_2). The other 35% remained as gaseous hydrocarbon, with the largest fraction being methane. Less than 2% of the carbon remained in the liquid phase. Table 2 presents the gas effluent analyses and adjusted values for CS3 assuming that the CO_2 levels would be equivalent if more time was given for release of the CO_2 from the liquid. Table 2 also contains results and adjusted values for a SCWG test of a mixture of primary and secondary sewage sludge. The results for the sewage sludge test are very similar to the compost test results. This indicates that the addition of municipal solid waste and composting did not significantly alter the SCWG process compared to treatment of only sewage sludge.

Liquid analyses were also obtained for tests CS-3 and CS-5. Table 3 presents the feed analysis and the values adjusted for dilution to 40 wt% solids. Table 4 presents the ash analysis. Table 5 presents the effluent analyses and the TOC for a SCWG test of a mixture of primary and secondary sewage sludge. The feed contained 16.8% TOC, and the effluent contained 0.25% TOC, which corresponds to 98.5% conversion. The effluent contained ~10 wt% solids, which was close to the expected value of 11.5 wt% ash content of the slurry feed. The pH of the effluent was 7.7. There was no nickel or chrome in the effluent, which corroborates the visual observation that there was no observable corrosion of the high nickel alloy preheater, reactor, or effluent heat exchanger. There was a small amount of soluble iron (2–4 ppm) in the effluent which is consistent with the feed ash analysis which shows a high iron content. Again, sewage sludge SCWG result is not significantly different from the compost SCWG results. The slightly lower TOC is probably due to the lower initial feed concentration for the sewage sludge test.

TABLE 1
SUMMARY OF ALL SCWG TESTS

Test	Date	Feed	Preheat	Reactor	Effluent	Comments and Results
S-1 Test plan configuration		Water and nitrogen	Ambient	Ambient	NA	Could not maintain pressure with gas through control valve. The liquid effluent a foam from the dissolved gas. (No data file)
S-2 Move pressure letdown before GLS. Operate GLS at 300 psig		Water and nitrogen	350	550	NA	Good pressure control. Liquid effluent still contains a lot of gas. (10289906.dat)
CS-1, Remove lower reactor thermocouple. Move upper thermocouple to the lower position.	11-15	Compost Slurry	300	525	NA	Preheater plugged with solids at the final thermocouple location. (11159912.dat – 15:29)
CS-2, Pull all thermocouples in 1/4 inch tubing back so that they do not restrict the flow.	11-16	Compost Slurry	300	525		Let-down valve and lines plugged with black solids. (11169912.dat – 15:59)
CS-3 Sample collection via reverse syringe pump. Prior to sample use dilution/settling chamber	11-24	Compost Slurry	300	625	Black slurry. Filtered effluent is reddish brown liquid. 300 scc/min gas.	Effluent lines plugged after 50 minutes despite dilution/settling chamber. Collect sample for 20 minutes. (11249912.dat – 14:17)
CS-4 Straightened tubing from RX outlet to dilution/settling chamber. Improved dilution/settling chamber. Moved PT-600 to inlet of dilution/settling chamber.	12-2	Compost Slurry	300	625	No effluent.	Plugged after effluent switched to sample syringe due to operator error (neglected to pre-pressurize sample syringe) (12029912.dat – 12:33)
CS-5 Same as CS-4	12-3	Compost Slurry	300	625	Same as CS-3 (effluent from CS-3 and CS-5 sent for gas and liquid analysis)	Effluent lines plugged after 44 min. of run time (23 min. to sample syringe). (12039912.dat – 14:04)

All feeds were fed at 17.5 ml/min.

TABLE 2
GAS ANALYSES FOR CS3 AND CS5 WITH ADJUSTED VALUES FOR CS3 ASSUMING AN EQUAL AMOUNT OF CO_2 WOULD HAVE BEEN RELEASED IF MORE TIME WAS ALLOWED FOR EQUILIBRATION

Species	CS3	CS5	CS3 adjusted	Prior Sewage Sludge Tests	Sewage Tests Adjusted
H2	12%	11%	8%	26%	15%
CH4	24%	16%	17%	28%	17%
CO	18%	7%	12%	11%	7%
CO2	28%	56%	56%	24%	56%
THC	9%	10%	6%	8%	5%
Total	91%	99%	100%	97%	100%

TABLE 3
COMPOST SLURRY COMPOSITION

Moisture	60.0 wt%
Ash	11.5 wt% (including oxides)
Carbon	16.8 wt%
Hydrogen	1.6 wt% (calculated)
Oxygen	9.5 wt%
Nitrogen	0.3 wt%
Sulfur	0.1 wt%
Chlorine	0.2 wt%
Total =	100 wt%

TABLE 4
ULTIMATE ANALYSIS OF THE FEED ASH HAS ALSO BEEN PROVIDED BY EESI, AS FOLLOWS

P	0.6 % by weight of total compost
K	0.2 % by weight of total compost
Mg	0.2 % by weight of total compost
Ca	1.9 % by weight of total compost
Na	0.4 % by weight of total compost
Fe	2.1 % by weight of total compost
Al	1.3 % by weight of total compost
O	16.7 % by weight of total compost
Total =	23.4 % by weight of total compost

TABLE 5
LIQUID EFFLUENT ANALYSIS

Liquid Tests	CS-3L	CS-5L	Prior Sewage Sludge
Total organic carbon (TOC mg/kg))	2,630	2,540	1,350
pH	7.66	7.81	
Metals: Cr (mg/kg)	<0.01	<0.01	
Metals: Ni (mg/kg)	<0.04	<0.04	
Metals: Fe (mg/kg)	1.52	3.86	
Total suspended solids (TSS)	Not Measured	93000	Not measured

2.2.2. Narrative Test Description

Shakedown testing was performed with water and nitrogen. During the initial testing, pressure control via the gas phase was inadequate, and there was too much gas in the liquid phase that exited the gas-liquid separator. The pressure control problem was caused because the flows in the system were so low that the smallest control valve on-hand could not maintain adequate back-pressure. The gas-liquid separator was moved down-stream of the control valve so that both the liquid and the gas went through the valve, and then pressure control was attained. The improved pressure control enabled good temperature control as well.

Testing with solid-containing material was then conducted. Initial testing with other solids containing feeds indicated that reactor could easily be plugged at the point where the lower thermocouple entered the reactor. This thermocouple was removed and the upper reactor thermocouple was extended to the normal position of the lower thermocouple. The first test with compost was then conducted. During the test, the preheater became plugged with solids at an internal thermocouple location. After the test, all internal thermocouples in 1/4" outer diameter lines were moved into the tees such that they did not restrict the flow.

The second test with compost slurry was then conducted. The change in thermocouple position prevented plugging at the thermocouple locations. However, the pressure let-down valve could not handle the solids produced, nor could the liquid control valve which maintained the level in the gas-liquid separator. While the pressure let-down and gas-liquid separator configurations have been used successfully with solids in larger systems, the small flows and orifice sizes of the laboratory equipment prevented repeating this success in the laboratory-scale system. Thus, an alternative pressure let-down system was employed to enable operation with solids on such a small-scale.

The alternative system consisted of passing the effluent through a dilution/settling chamber up-stream of the let-down, and then collecting the sample in a reverse syringe pump after steady-state was attained. This effluent system allowed operation long enough to collect gas and liquid samples (50 minutes on feed), but the effluent lines still plugged. The lines were straightened as much as possible remove potential plugging locations. The next test failed because the sample syringe cylinder was not pre-pressurized. A final test was the conducted which repeated the results of the third test. Unfortunately, the effluent line plugged at the entrance to the flow valve for switching between the settling chamber and the sample syringe.

3. CONCLUSIONS AND RECOMMENDATIONS

The testing provided proof-of-principle data that portray an excellent prognosis for application of SCWG to composted municipal solid waste and sewage sludge mixtures. The feed preparation and pumping tests demonstrated a scaleable feed method with slurry concentrations nearly double the goal for the project. Nearly all of the major challenges to SCWG of compost were overcome during the laboratory-scale SCWG tests. All problems encountered during the testing were directly related to operating such a small-scale system with a large ash fraction in the feed. Solutions to these problems have already been demonstrated for feeds with much higher ash fractions in GA's larger SCWO systems. These solutions will be easily transferred to larger SCWG systems.

Nearly all of the major challenges to SCWG were answered positively. Pilot-scale testing is the next logical step for the development of this process toward commercial-scale facilities. This testing will enable more stable operation using GA's solids handling methods proven in SCWO systems. Operation can then be demonstrated for longer operating times, and quantitative process data will be obtained to enable thorough analysis of a commercial system and subsequent design of such a system. Table 6 lists the challenges, the current test results, and the likely next step.

4. REFERENCES

1. "Supercritical Water Gasification of Biomass/RDF Compost Test Plan", GA Doc. No. 39037-901 N/C, October 1999.

TABLE 6
RESULTS AND RECOMMENDATIONS FOR EACH OF THE MAJOR COMPOST SCWG CHALLENGES

Challenge	Laboratory-scale test results	Next step for pilot-scale testing
Slurry preparation	40 wt% size-reduced slurry	Continuous feed to a slurry preparation module. Determine maximum concentration.
Pumping slurries	Easily pumped the slurry in a syringe pump.	Continuous operation with GA's slurry pump.
Solids handling	Demonstrated operation with no plugging of the preheater, heat exchanger, or reactor. Needed to use special pressure-let down system which still plugged during the testing.	Demonstrate operation in larger-scale equipment. Demonstrate GA's SCWO solids handling equipment on a pilot-scale SCWG system.
Corrosion	Little or no corrosion was observed.	Utilize larger-scale equipment to obtain longer-term operation to verify adequate corrosion resistance.
Char and tar formation	Little char or tar formation was observed.	Operate a larger-scale system to enable quantification of the char and tar formation. Determine if separation from the effluent and feed to SCWO is warranted.
Gasification efficiency	Gasification efficiency of approximately 98% was observed.	Obtain more uniform operating conditions by using larger-scale equipment compatible with GA's SCWO solids handling equipment, Parameterize gasification efficiency on temperature, pressure, and residence time. Consider utilizing sludge/waste mixture earlier in the process after less composting has occurred.

APPENDIX II

BACKGROUND INFORMATION

NOMENCLATURE

Δe_x = change in exergy in a heat exchanger or turbine
h_1 = enthalpy of entering stream
h_2 = enthalpy of exiting stream
s_1 = entropy of entering stream
s_2 = entropy of exiting stream
T_o = absolute ambient temperature

Introduction

The major advantage of coal/biomass slurries is the ability to transport them over long distances, to feed pressurized energy recovery systems and to recover energy from the excess water.

As long ago as 1891 a patent was issued for a method of pumping coal and water (Wasp 1971). In 1957, the 10-inch, 108-mile Consolidation Coal line and the 6-inch, 72 mile American Gilsonite line marked the beginning of long-distance slurry lines in the U.S. In 1970, the 18-inch, 273 mile Black Mesa line was installed to feed the Mohave power plant (Elliot, 1981). This system provides all the fuel requirements for two 750-MW generating units in southern Nevada (about 5 million tons/year). The project is significant in that it was the first generating facility designed to use coal slurry directly from the start of operations. Availability of the Black Mesa pipeline system has been on the order of 99%. There are no significant technical problems in the slurry system.

Thermal coal is well suited to pipeline transport because it must be ground until approximately 70-80% can pass through 200 mesh before it is blown into the boiler. Coal pipeline hydraulics require all material to pass through about 20 mesh. Therefore the slurry fineness requirements simply cause the required size reduction to be split, some at the head end of the pipeline and the remainder at the power plant. Coal grinding normally involves conventional milling equipment. For example, the Black Mesa system employs rod mills to produce the required particle size distribution. Typical pipeline coal slurry specifications are shown in Table 1.

Table 1 Coal Slurry Specifications

	Concentration, %	
Mesh	Ohio	Black Mesa
+14	1-3	0-2
-100	35-40	35-45
-325	18-20	18-20

The required pipe diameter can also be calculated as follows:

$$\mathbf{D = 0.01365\ (TPY/WH\ \rho_s\ V)^{0.5}},$$

where D = required internal pipe diameter (in.),
TPY = annual requirement of bone-dry coal (short tons),
W = bone-dry solids (wt), (expressed as a fraction),
H = number of operating hours per year,
V = bulk velocity (ft/s), and
ρ_s = density of slurry.

Slurry Preparation

Feed preparation covers the physical and chemical processing necessary to give the slurry characteristics required for hydraulic transport and use. Preparation normally involves both size reduction (crushing and grinding) and addition of the liquid phase. Chemical treatment may also be part of slurry preparation for corrosion inhibition, thinning, and improving the characteristics of the final product. In the case of coal transport, a particle size specifically suited for slurry transportation must be produced (Cowper 1972). A balance has to be made between pumpability and dewatering characteristics. If sizing is too fine, pumpability may be good but the slurry may be difficult to dewater. The fine particles can have higher ash content than the parent coal. If the particles are too course, the slurry must be pumped above the critical velocity to maintain suspension, and costs due to pressure drop and erosion may be excessive. For gasification systems, top size particles can be only partially reacted in entrained gasifiers and can produce excessive carbon in the ash, lowering efficiency and presenting disposal problems.

Typical specifications for a coal slurry system with a 95% operating factor are 5.5 ft/s velocity and 50% concentration of solids by weight (Elliot, 1981). The effect of solids concentration on viscosity of coal slurry at 60F is shown in Fig. 1.

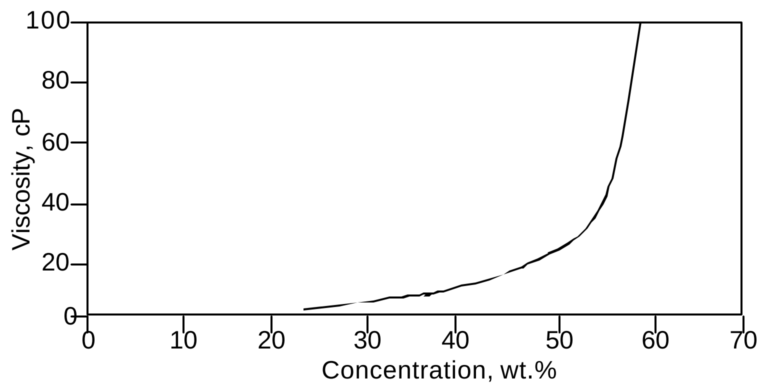

Fig. 1 Effect of Solids Concentration on Viscosity
for Coal Slurries (Thomas, 1965)

Virtually all slurries exhibit non-Newtonian behavior. There are several shear stress - velocity gradient curves that represent various slurries. The most common is probably Bingham plastic. In this behavior, the shear stress is a straight line with a shear stress higher than Newtonian. Pseudoplastic and dilatant behaviors are also possible. These possibilities require that slurries composed of biomass and coal are tested in a pilot system to predict operating parameters for larger systems. Process control can be improved by a test loop in the slurry preparation system, where particle size and concentration are measured in real time. A Coulter particle counter can be used for both measurements.

The Coulter LS Series delivers volume %, surface area % and particle size distributions that can be used to calculate weight %. The MS Windows software offers a data export function with 1% reproducibility that can be used to control slurry export to the transport and pumping systems.

Slurry Pumping

Multiple coal gasification plants operate GEHO piston diaphragm pumps for the transfer of coal slurry and for feeding the gasifier. Synthesis gas ($CO + H_2$) can be used to produce ammonia for fertilizers and oxo-chemicals. Slurried coal can be fed at up to 65% solids by weight at up to 300 bar (4,500 psig) at up to 40 US gpm. GEHO feed pumps have on-line proven performance within ± 1% accuracy over a wide range of operating conditions at up to 95% efficiency. This performance is the result of proper sizing of the pump, suction and discharge dampeners, valves and speed controls.

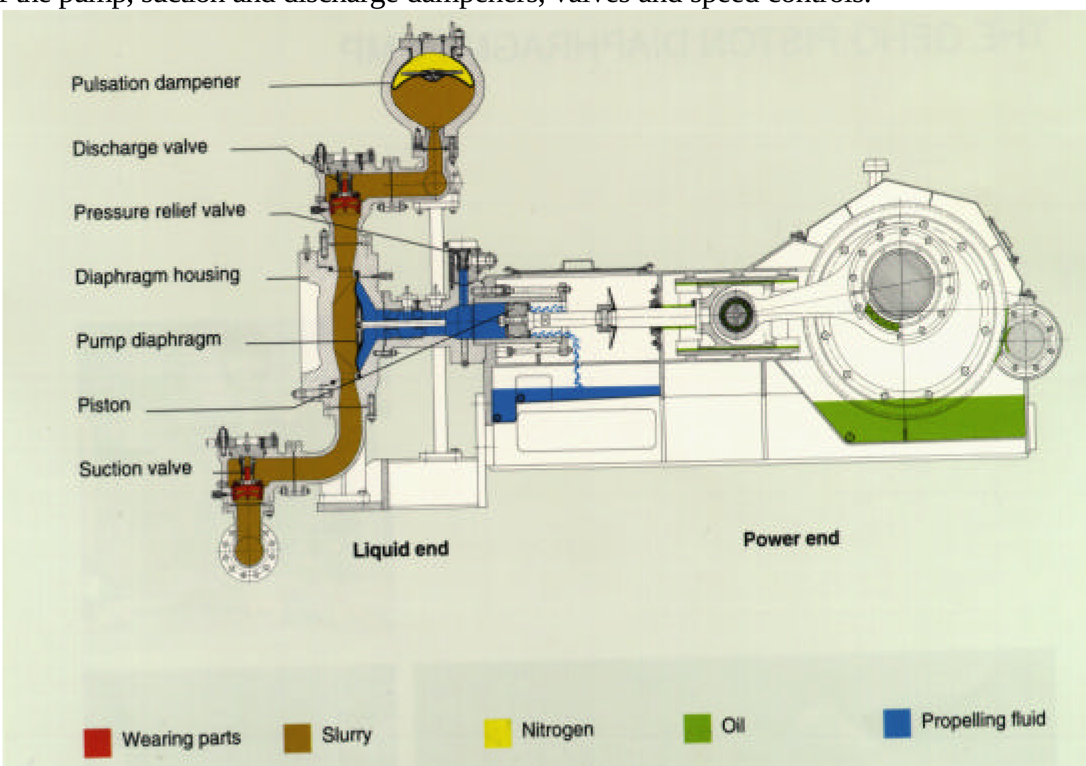

Fig. 2 GEHO TZPM piston diaphragm pump.

Biomass/Coal Slurries

In addition to water required to prepare a biomass slurry, biomass generally has very high inherent moisture. For example sewage sludge from secondary treatment can have over 80% inherent moisture and cannot be easily pumped above 12-14% solids in a slurry. EnerTech Environmental has designed a sewage sludge carbonization facility for South Kearney, NJ to produce a fuel oil substitute having about 50% moisture by weight. EESI and General Atomics (GA) have produced a pumpable biomass slurry containing over 40% solids by weight from compost. The compost was prepared in a Bedminster aerobic digester from two-thirds municipal packer truck waste and one-third by weight of about 18% solids sewage sludge.

Coal can be used to increase the concentration, or "energy density" of biomass slurries. For example a slurry composed of about 50% coal and compost and 50% water may be a practical limit for these slurries. For conventional combustion systems, oxygen and inherent moisture that are chemically bound in the coal particles reduce heat value and efficiency. In conventional gasification systems, such as the Texaco process, water in the feed reduces efficiency because all of the water must be evaporated in the reactor by burning additional coal with oxygen. Excess water is subsequently condensed at low efficiency. These processes require maximum practical concentrations to have any hope of meeting Vision 21 goals.

Energy Recovery from Slurries

The ability of steam to perform useful work is called availability or exergy. Exergy analysis uses the formula

$$\Delta e_x = h_1 - h_2 - T_o (s_1 - s_2), \qquad (1)$$

Exergy analysis indicates that exergy loss is proportional to the heat transferred and the temperature difference across the heat transfer surface. Exergy analysis shows that <u>over fifty percent of the ability of fuels to perform useful work is lost in conventional low-pressure steam generators</u>.

As we have seen, inherent moisture and slurry moisture also subtract from the efficiencies of conventional combustion and gasification systems, where the resulting excess moisture in the products does not produce significant energy. In low-pressure systems, this is just the difference between the lower heating value (LHV) and the higher heating value (HHV) minus the heat required to evaporate the feed moisture and bring it to the exhaust condition. For example, the LHV of Illinois No. 6 coal is about 10,500 Btu/lb at 10% inherent moisture and about 11,000 Btu/lb HHV. The heating value of 50% solids slurry using this coal can be calculated by reducing the combustible solids by half to about 5,250 Btu/lb, and subtracting the heat required to evaporate 0.5 lb of water and discharge it as vapor at exhaust conditions, say 350 F. and 14.7 psia. This enthalpy of the excess moisture in the exhaust is about

1,150 + 65 = 1,215 Btu/lb.

The net LHV of the slurry is then

5,250 - 1,215 x 0.5 = 4,640 Btu/lb.

The HHV of the slurry adds back the enthalpy of the excess moisture, resulting in a value of about

11,000 ÷ 2 = 5,500 Btu/lb.

Note that the difference between LHV and HHV is much larger in the slurry than the raw coal. The concentration of a slurry of Illinois No. 6 coal that has no net LHV can be calculated with

10,500 x C - 1,215 x (1 - C) = 0,

resulting in C = 10.4%. The HHV at this concentration is
11,000 x C = 1,140 Btu/lb.

LHV is used more often in Europe, where the lack of recovery of energy from discharge moisture in conventional energy systems is realized. This illustrates the errors that may be associated with using either LHV or HHV to calculate efficiency in conventional slurry-fed energy systems.

A more useful concept is *exergy*, used in ASME "thermoeconomic" analysis. For example, the exergy of Illinois No. 6 coal is about 11,350 Btu/lb, or 3% higher than the HHV. The exergy of slurries is slightly higher than the HHV of the slurries, as illustrated above.

Combined Cycle Systems

A typical combined-cycle gas turbine system is shown in Figure 3.

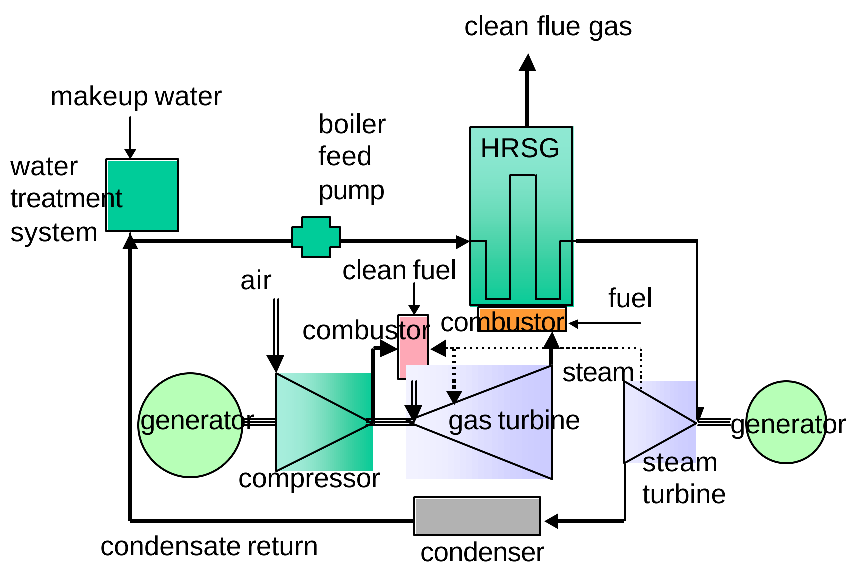

Fig. 3 Combined Cycle System

This configuration is limited to clean fuels and produces electricity at over 50% efficiency. Excess air is used to control turbine inlet temperature at the cost of additional power required for the compressor. Steam is produced in a conventional HRSG that can operate at over 100 bar (1500 psia) and over 540 C (1000 F). HRSGs are available in once-through design (without drum), with alloy 800H tubes that have fins for improved heat transfer from combustion products. Steam can be extracted from the steam turbine and injected to control NOx emissions and cool the high-temperature turbine blades. Additional steam can be injected to significantly increase power output, as in the dual-fluid or Cheng cycles. This steam replaces excess air, lowering compressor flow rate. Steam increases the specific heat of the gases in the turbine, increasing turbine power. Feedwater must be very clean to avoid corrosion and deposition on the gas turbine blades.

Conventional simple cycle gas-fired turbines operate at overall cycle efficiencies of 30-42%. Efficiencies of existing aeroderivative systems can be increased to above 50% by incorporating intercooling, higher firing temperatures/pressure ratios and steam injection. New GTCC plants with turbine inlet temperatures as high as 2600°F are coming on-line that are designed to operate at overall cycle efficiencies of 58-60%.

Hybrid Systems

Fuel cells are now being demonstrated with cycle efficiencies over 50%. Electric conversion efficiencies above 70% are forecast for hybrid fuel cell / advanced turbine systems by 2010, as shown in Fig. 4.

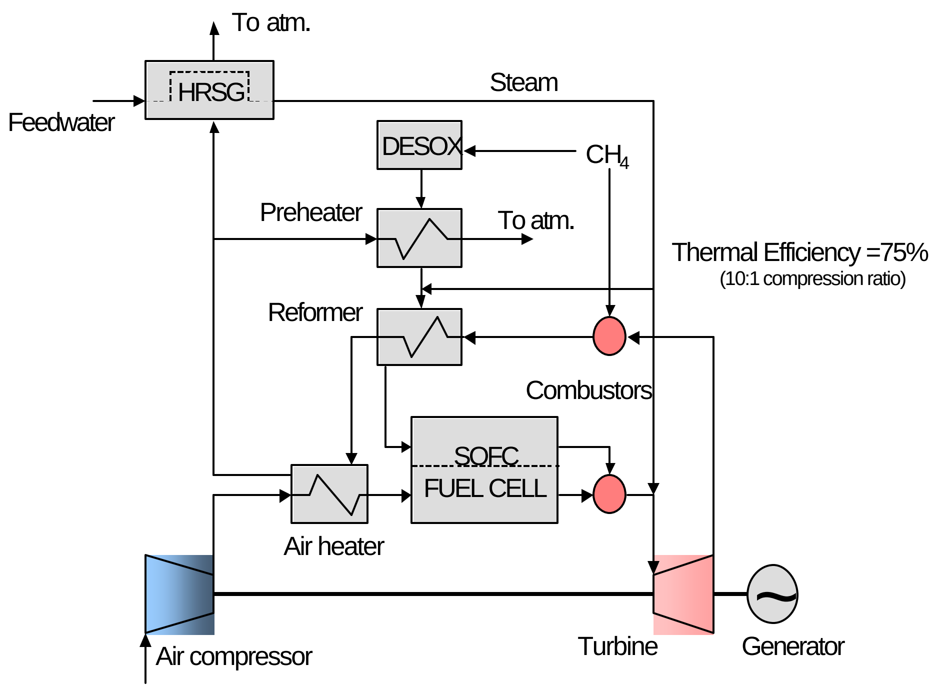

Fig. 4 Hybrid SOFC - Gas Turbine Combined Cycle System

© 2000 by EESI

after Massardo, A.F.& Lubelli, F., ASME Journal of Engineering for Gas Turbines and Power, Jan. 2000

This example does not provide for differences in fuel cell and turbine capacities and none of the systems analyzed can operate with solid fuels, such as coal, biomass and opportunity fuels unless they are first converted to fuel gas. High-pressure operation, generally above about 400 psig, requires slurry feeding that offers the possibility of recovering energy from excess moisture in the feed. For example, if the steam produced in the combustion or gasification of slurries is at pressure, a turbine or expander can be used to return the gases to fuel cell and gas turbine inlet pressure to recover more of the energy in the fuel. In addition to smaller size, this is a major advantage of pressurized fluid bed combustion and gasification systems. This is the basis of the efficiency of integrated gasification combined cycle (IGCC) systems. IGCC power plants with conventional turbine inlet temperatures of 2000°F operate at overall cycle efficiencies of 40-44% when processing coal.

The Vapor Transmission Cycle

A simplified VTC concept is shown in Figure 5.

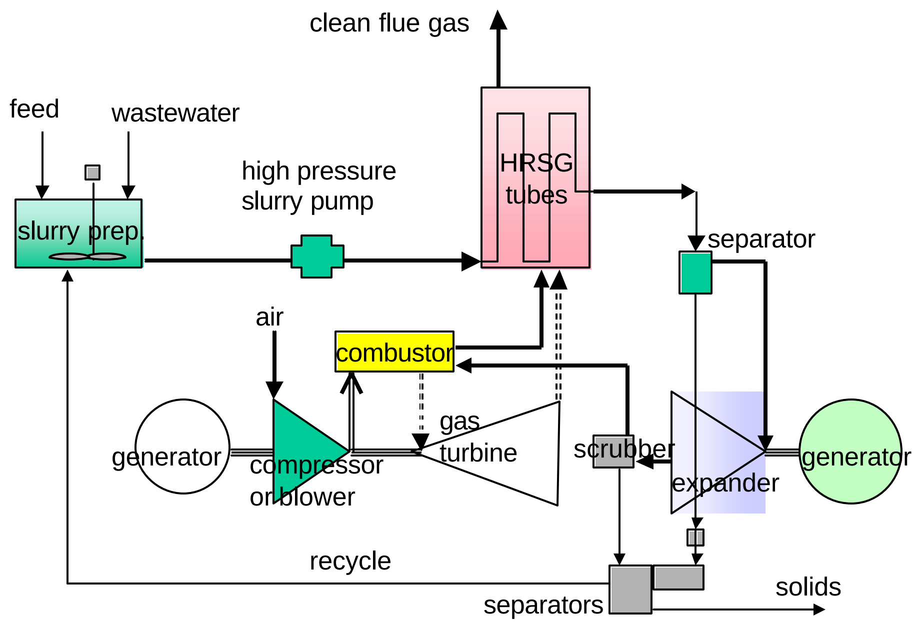

Fig. 5 Simplified Vapor Transmission Cycle Concept

This concept incorporates supercritical water gasification in HRSG tubes with a compressor and gas turbine, or in an existing steam plant with a blower to supply combustion air at low pressure. Emissions are minimized by two cleaning stages. Liquid effluents are eliminated by recycling condensate back to slurry preparation. This concept will be thoroughly evaluated using test data and thermoeconomic analysis in Stage 4.

Life Cycle Costs

Preliminary life-cycle cost analyses have been prepared for 50MW model plants capable of serving cities of 250,000 to 300,000 population. A preliminary baseline cost analysis for a new 50MW natural gas fired combined cycle plant operating in peaking service (3,600 hrs/year) at 60% thermal efficiency is shown in Figure 6. Natural gas cost is assumed to be $3.00/million Btu and capital cost is assumed to be $500/kW. The analysis predicts that average revenue must be $100/MWh to pay back the capital investment within five years.

The same natural gas fired combined cycle plant operating in base load service (7,200 hrs/year) is shown in Figure 7. This analysis predicts that average revenue must be $58/MWh to pay back the capital investment within five years.

For compost feed, each model plant will handle about 300 tons/day of municipal packer truck waste (MSW) and 100 tons/day of secondary sewage sludge at 18% solids. Disposal fees must be sufficient to pay the capital investment, operating and maintenance costs, resulting in a compost fuel price of $1.00/million Btu. This price is similar to delivered costs for coal.

Bedminster Bioconversion of Georgia has justified the construction of six operating composting plants without a guaranteed compost price. A separate life cycle cost analysis was not prepared for compost plants for this project. Co-locating composting plants with VTC power facilities at municipal landfills will allow land reclamation through mining existing refuse, eliminate compost curing, and allow wet compost to be used for power generation at lower cost.

For comparison with the natural gas plant, Fig. 8 shows a preliminary life cycle cost analysis for a new VTC plant fed by compost at $1.00/million Btu. This analysis predicts that average revenue must be $100/MWh to pay back the capital investment within five years. This is the same revenue required for the natural gas plant operating in peaking service.

A similar life cycle cost analysis has been prepared for retrofit of VTC equipment to an existing natural gas fired combined cycle plant operating in base load service, shown in Fig. 9. Capital costs are for the retrofit equipment only, assumed equal to the entire cost of the natural gas plant. This analysis predicts that average revenue must be $50/MWh to pay back the capital investment within five years, lower than any of the other costs evaluated.

Improvements in efficiency through process optimization, reductions in fuel costs for wastes through disposal fees, and byproduct sales, will all improve the operating economics. The VTC system promises to reduce power costs, while maintaining the advantages of natural gas fired systems.

Preliminary Life Cycle Cost Analysis - 50 MW Natural Gas Fired Combined Cycle Plant - Peaking Service

Based on G.E. LM2500 STIG

Assumed Discount Rate		10	%											
Assumed Inflation rate		3	%/year		**Present Value, US$millions (rounded to nearest US$100,000)**									
		Project Year	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
Capital Cost		**millions $US**	**$25**	**10 Year financing (including contingency)**										
Payments	Interest Rate, %	10	-4.1	-3.8	-3.6	-3.3	-3.1	-2.9	-2.7	-2.6	-2.4	-2.3	0.0	0.0
Operating Costs	**(3% 0f capital costs)**		CONSTRUCTION in 2003											
Labor & Supervision				-0.7	-0.7	-0.6	-0.6	-0.5	-0.5	-0.5	-0.4	-0.4	-0.4	-0.4
Maintenance Costs	**(4% 0f capital costs)**													
Labor				-0.5	-0.4	-0.4	-0.4	-0.4	-0.3	-0.3	-0.3	-0.3	-0.3	-0.2
Materials				-0.5	-0.4	-0.4	-0.4	-0.4	-0.3	-0.3	-0.3	-0.3	-0.3	-0.2
Feed materials costs and fees														
Catalysts & chemicals	$/tonne	0		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Consumption	TPY	0												
Fuel Costs	$/Mbtu	**3.00**		-2.9	-2.7	-2.5	-2.4	-2.2	-2.1	-1.9	-1.8	-1.7	-1.6	-1.5
Consumption	MBtuh	285												
Residue disposal costs	$/tonne	0		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Quantity to landfill	TPY	0												
Total Expense		**millions $US**	**-4.1**	**-8.3**	**-7.8**	**-7.3**	**-6.8**	**-6.4**	**-6.0**	**-5.6**	**-5.3**	**-4.9**	**-2.5**	**-2.3**
Revenue	MWh/Yr.	180,000	CONSTRUCTION in 2003											
Power sales	$/MWh	**100**		16.9	15.8	14.8	13.8	13.0	12.1	11.4	10.6	10.0	9.3	8.7
Disposal fees	$/ton	**0**		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Consumption	wet TPY	0												
Byproduct sales	$/tonne	**0**		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Production	TPY	0												
Total Revenue		**millions $US**	**0.0**	**16.9**	**15.8**	**14.8**	**13.8**	**13.0**	**12.1**	**11.4**	**10.6**	**10.0**	**9.3**	**8.7**
Discounted Cash Flow			-4.1	8.5	8.0	7.5	7.0	6.6	6.1	5.7	5.4	5.0	6.8	6.4
Cumulative Cash Flow		**millions $US**	**-4**	**4**	**12**	**20**	**27**	**33**	**40**	**45**	**51**	**56**	**63**	**69**
							Capital cost recovered							

Note: Average power output = **50** MW
Capital cost = **500** $ per kW installed
Efficiency assumed = **60** % to electric power

Fuel cost assumed = **3.00** $/MJ (~million Btu)
Power sales assumed = **100** $/MWh
Operating hours assumed = **3600** per year

Figure 6

Preliminary Life Cycle Cost Analysis - 50 MW Natural Gas Fired Combined Cycle Plant - Base Load Service

Based on G.E. LM2500 STIG

Assumed Discount Rate: 10 %

Assumed Inflation rate: 3 %/year

Present Value, US$millions (rounded to nearest US$100,000)

		Project Year	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
Capital Cost		**millions $US**	**$25**	**10 Year financing (including contingency)**										
Payments	Interest Rate, %	10	-4.1	-3.8	-3.6	-3.3	-3.1	-2.9	-2.7	-2.6	-2.4	-2.3	0.0	0.0
Operating Costs	**(3% 0f capital costs)**		CONSTRUCTION in 2003											
Labor & Supervision				-0.7	-0.7	-0.6	-0.6	-0.5	-0.5	-0.5	-0.4	-0.4	-0.4	-0.4
Maintenance Costs	**(4% 0f capital costs)**													
Labor				-0.5	-0.4	-0.4	-0.4	-0.4	-0.3	-0.3	-0.3	-0.3	-0.3	-0.2
Materials				-0.5	-0.4	-0.4	-0.4	-0.4	-0.3	-0.3	-0.3	-0.3	-0.3	-0.2
Feed materials costs and fees														
Catalysts & chemicals	$/tonne	0		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Consumption	TPY	0												
Fuel Costs	$/Mbtu	**3.00**		-5.8	-5.4	-5.0	-4.7	-4.4	-4.1	-3.9	-3.6	-3.4	-3.2	-3.0
Consumption	MBtuh	285												
Residue disposal costs	$/tonne	0		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Quantity to landfill	TPY	0												
Total Expense		**millions $US**	**-4.1**	**-11.2**	**-10.5**	**-9.8**	**-9.2**	**-8.6**	**-8.1**	**-7.6**	**-7.1**	**-6.6**	**-4.1**	**-3.8**
Revenue	MWh/Yr.	360,000	CONSTRUCTION in 2003											
Power sales	$/MWh	**58**		19.6	18.3	17.1	16.1	15.0	14.1	13.2	12.3	11.6	10.8	10.1
Disposal fees	$/ton	**0**		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Consumption	wet TPY	0												
Byproduct sales	$/tonne	**0**		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Production	TPY	0												
Total Revenue		**millions $US**	**0.0**	**19.6**	**18.3**	**17.1**	**16.1**	**15.0**	**14.1**	**13.2**	**12.3**	**11.6**	**10.8**	**10.1**
Discounted Cash Flow			-4.1	8.3	7.8	7.3	6.9	6.4	6.0	5.6	5.3	4.9	6.7	6.3
Cumulative Cash Flow		**millions $US**	**-4**	**4**	**12**	**19**	**26**	**33**	**39**	**44**	**50**	**55**	**61**	**68**
							Capital cost recovered							

Note:

Average power output =	**50**	MW
Capital cost =	**500**	$ per kW installed
Efficiency assumed =	**60**	% to electric power
Fuel cost assumed =	**3.00**	$/MJ (~million Btu)
Power sales assumed =	**58**	$/MWh
Operating hours assumed =	**7200**	per year

Figure 7

Preliminary Life Cycle Cost Analysis - 50 MW Biomass Combined Cycle Plant - Base Load Service

Based on G.E. LM2500 STIG

Assumed Discount Rate		10	%											
Assumed Inflation rate		3	%/year			**Present Value, US$millions (rounded to nearest US$100,000)**								
		Project Year	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
Capital Cost		**millions $US**	**$55**	**10 Year financing (including contingency)**										
Payments	Interest Rate, %	10	-9.0	-8.4	-7.8	-7.3	-6.9	-6.4	-6.0	-5.6	-5.3	-5.0	0.0	0.0
Operating Costs	**(4% 0f capital costs)**		CONSTRUCTION in 2003											
Labor & Supervision				-2.1	-1.9	-1.8	-1.7	-1.6	-1.5	-1.4	-1.3	-1.2	-1.1	-1.1
Maintenance Costs	**(6% 0f capital costs)**													
Labor				-1.5	-1.4	-1.4	-1.3	-1.2	-1.1	-1.0	-1.0	-0.9	-0.9	-0.8
Materials				-1.5	-1.4	-1.4	-1.3	-1.2	-1.1	-1.0	-1.0	-0.9	-0.9	-0.8
Feed materials costs and fees														
Catalysts & chemicals	$/tonne	100		-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
Consumption	TPY	1,118												
Fuel Costs	$/Mbtu	**1.00**		-1.9	-1.8	-1.7	-1.6	-1.5	-1.4	-1.3	-1.2	-1.1	-1.1	-1.0
Consumption	MBtuh	285												
Residue disposal costs	$/tonne	20		-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.2	-0.2	-0.2	-0.2	-0.2
Quantity to landfill	TPY	18627												
Total Expense		**millions $US**	**-9.0**	**-15.9**	**-14.9**	**-13.9**	**-13.1**	**-12.2**	**-11.4**	**-10.7**	**-10.0**	**-9.4**	**-4.2**	**-3.9**
Revenue	MWh/Yr.	360,000	CONSTRUCTION in 2003											
Power sales	$/MWh	**100**		33.7	31.6	29.6	27.7	25.9	24.3	22.7	21.3	19.9	18.7	17.5
Disposal fees	$/ton	**0**		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Consumption	wet TPY	0												
Byproduct sales	$/tonne	**0**		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Production	TPY	0												
Total Revenue		**millions $US**	**0.0**	**33.7**	**31.6**	**29.6**	**27.7**	**25.9**	**24.3**	**22.7**	**21.3**	**19.9**	**18.7**	**17.5**
Discounted Cash Flow			-9.0	17.8	16.7	15.6	14.6	13.7	12.8	12.0	11.2	10.5	14.5	13.6
Cumulative Cash Flow		**millions $US**	**-9**	**9**	**26**	**41**	**56**	**69**	**82**	**94**	**105**	**116**	**131**	**144**
							Capital cost recovered							

Note:

Average power output = **50** MW

Capital cost = **1,100** $ per kW installed

Efficiency assumed = **60** % to electric power

Fuel cost assumed = **1.00** $/MJ (~million Btu)

Power sales assumed = **100** $/MWh

Operating hours assumed = **7200** per year

Figure 8

Preliminary Life Cycle Cost Analysis - 50 MW Biomass Combined Cycle Retrofit - Base Load Service

Based on G.E. LM2500 STIG

Assumed Discount Rate		10	%											
Assumed Inflation rate		3	%/year		**Present Value, US$millions (rounded to nearest US$100,000)**									
		Project Year	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
Capital Cost		**millions $US**	**$25**	**10 Year financing (including contingency)**										
Payments Interest Rate, %		10	-4.1	-3.8	-3.6	-3.3	-3.1	-2.9	-2.7	-2.6	-2.4	-2.3	0.0	0.0
Operating Costs	**(4% 0f capital costs)**		CONSTRUCTION in 2003											
Labor & Supervision				-0.9	-0.9	-0.8	-0.8	-0.7	-0.7	-0.6	-0.6	-0.6	-0.5	-0.5
Maintenance Costs	**(6% 0f capital costs)**													
Labor				-0.7	-0.7	-0.6	-0.6	-0.5	-0.5	-0.5	-0.4	-0.4	-0.4	-0.4
Materials				-0.7	-0.7	-0.6	-0.6	-0.5	-0.5	-0.5	-0.4	-0.4	-0.4	-0.4
Feed materials costs and fees														
Catalysts & chemicals	$/tonne	100		-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
Consumption	TPY	1,118												
Fuel Costs	$/Mbtu	**1.00**		-1.9	-1.8	-1.7	-1.6	-1.5	-1.4	-1.3	-1.2	-1.1	-1.1	-1.0
Consumption	MBtuh	285												
Residue disposal costs	$/tonne	20		-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.2	-0.2	-0.2	-0.2	-0.2
Quantity to landfill	TPY	18627												
Total Expense		**millions $US**	**-4.1**	**-8.5**	**-8.0**	**-7.5**	**-7.0**	**-6.6**	**-6.1**	**-5.7**	**-5.4**	**-5.0**	**-2.6**	**-2.4**
Revenue	MWh/Yr.	360,000	CONSTRUCTION in 2003											
Power sales	$/MWh	**50**		16.9	15.8	14.8	13.8	13.0	12.1	11.4	10.6	10.0	9.3	8.7
Disposal fees	$/ton	**0**		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Consumption	wet TPY	0												
Byproduct sales	$/tonne	**0**		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Production	TPY	0												
Total Revenue		**millions $US**	**0.0**	**16.9**	**15.8**	**14.8**	**13.8**	**13.0**	**12.1**	**11.4**	**10.6**	**10.0**	**9.3**	**8.7**
Discounted Cash Flow			-4.1	8.3	7.8	7.3	6.8	6.4	6.0	5.6	5.3	4.9	6.7	6.3
Cumulative Cash Flow		**millions $US**	**-4**	**4**	**12**	**19**	**26**	**33**	**39**	**44**	**49**	**54**	**61**	**67**
							Capital cost recovered							

Note: Average power output = **50** MW
Capital cost = **500** $ per kW installed
Efficiency assumed = **60** % to electric power

Fuel cost assumed = **1.00** $/MJ (~million Btu)
Power sales assumed = **50** $/MWh
Operating hours assumed = **7200** per year

Figure 9

References

1. Wasp, E.J.; Thompson, T.L. and Snoek, P.E., "The Era of Slurry Pipelines," *Chem. Tech.*, 522-562 September, **1971**

2. Elliot, Martin A., Chemistry of Coal Utilization **1981,** 535-538

3. Cowper, N.T.; Thompson, T.L.; Aude, T.C.; Wasp, E.J., "Processing Steps: Keys to Successful Slurry Pipeline Systems," *Chem. Eng.*, 58-67, February **1972**

List of Figures

List of Tables